Sterile Neutrinos and the Global Reactor Antineutrino Dataset

Jeff Berryman, U. Kentucky/U.C. Berkeley

Based on:

PRD 101 (2020) 015008, arXiv:1909.09267 (w/ P. Huber);

arXiv:2005.01756 (w/ P. Huber; submitted to JHEP)

Outline

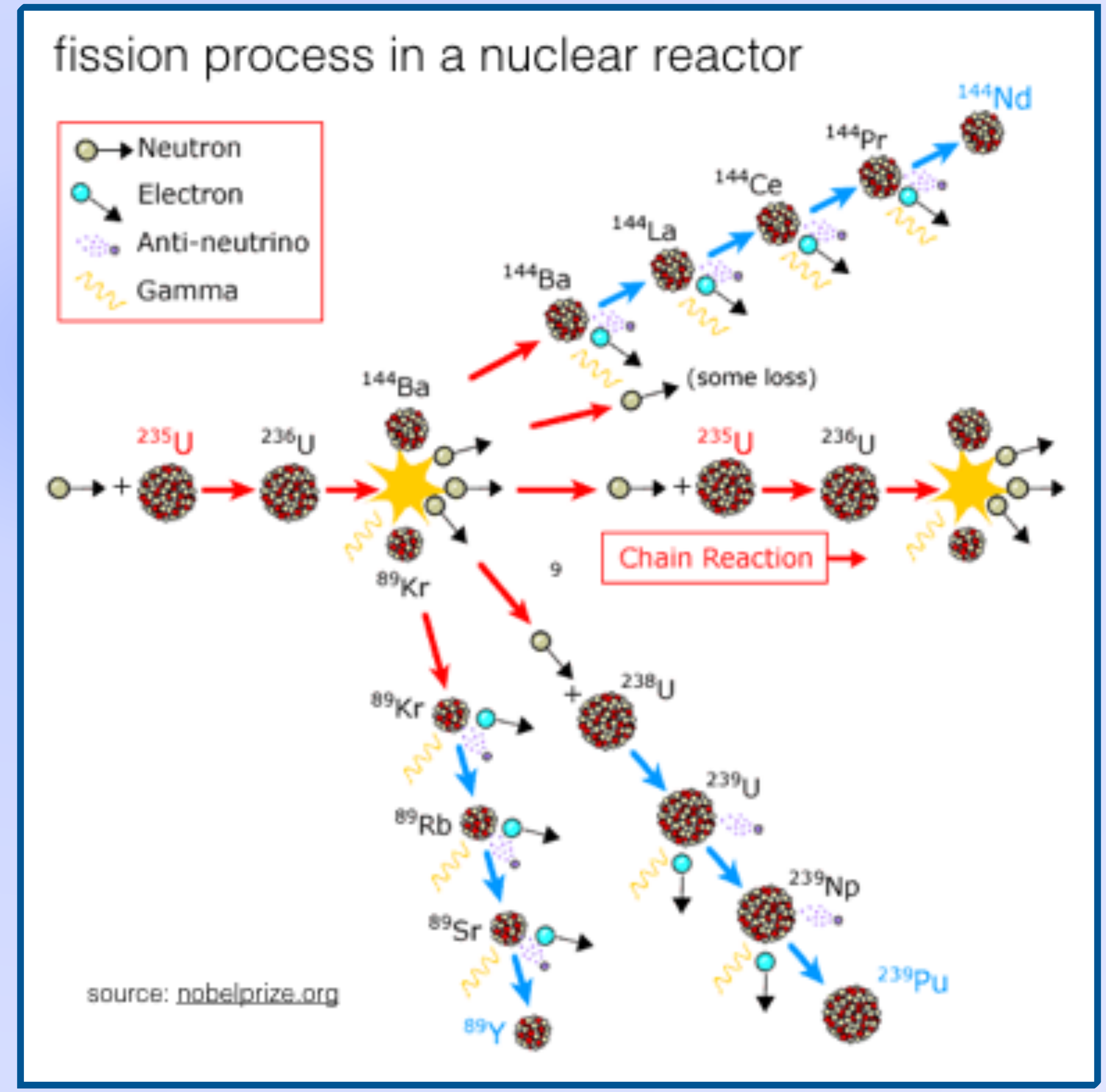
- *The Basic Ingredients – Fluxes, Cross Sections and Data*
  - Where Do Flux Predictions Come From?
- *Yet Another Global Fit...*
  - Rate Measurements
  - Spectrum Measurements
- *Where Do We Go From Here?*
  - The Short and Not-So-Short Terms

Part 1: Prolegomena

Antineutrinos from Reactors

Nuclear fission produces neutron-rich fission fragments; beta decays ensue!

Antineutrinos from nuclear reactors arise mainly from four isotopes:
^{235}U (>50%), ^{238}U (<8%), ^{239}Pu (<30%), ^{241}Pu (<6%)



Antineutrinos from Reactors

Producing a *prediction* for the spectrum of antineutrinos is *really, really difficult*!

Two basic approaches:

1. *Ab Initio Method*: Go to nuclear databases, add up all the beta decays of all the fission fragments.
2. *Conversion Method*: Measure the spectrum of *electrons* from fission fragments → use what we know about beta decay to infer the antineutrino spectrum

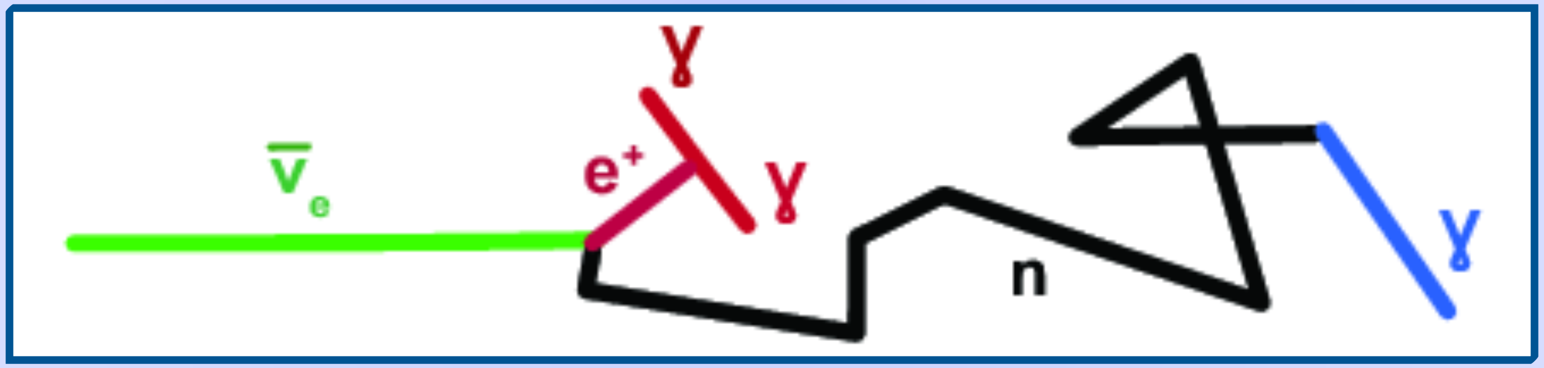
- The *Huber-Mueller (HM)* predictions use the latter technique

Th. A. Mueller, et al., PRC 83 (2011) 054615;
P. Huber, PRC 84 (2011) 024617 (Erratum: PRC 85 (2012) 029901)

Detecting Reactor Antineutrinos

- The classic detection process is *inverse beta decay (IBD)*

$$\boxed{\overline{\nu}_e + p^+ \rightarrow e^+ + n}$$



- *Magnetic moment* searches use antineutrino-electron scattering
  - Few experiments have actually made this measurement; not better than 25%! (*TEXONO, MUNU*)
- Also *O*(~10%) measurements of (charged- and neutral-current) *deuterium disintegration* – e.g., F. Reines @ Savannah River

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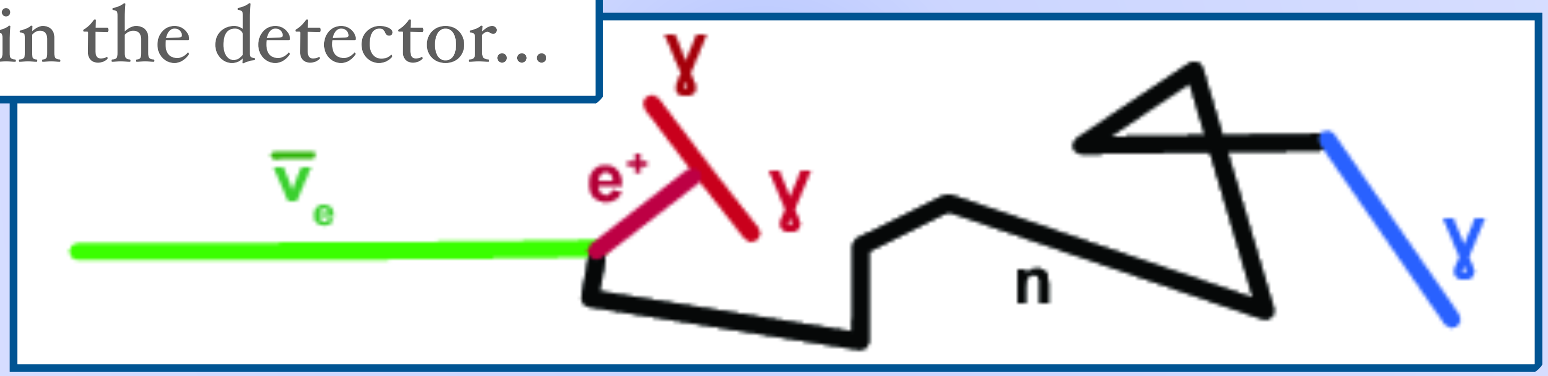

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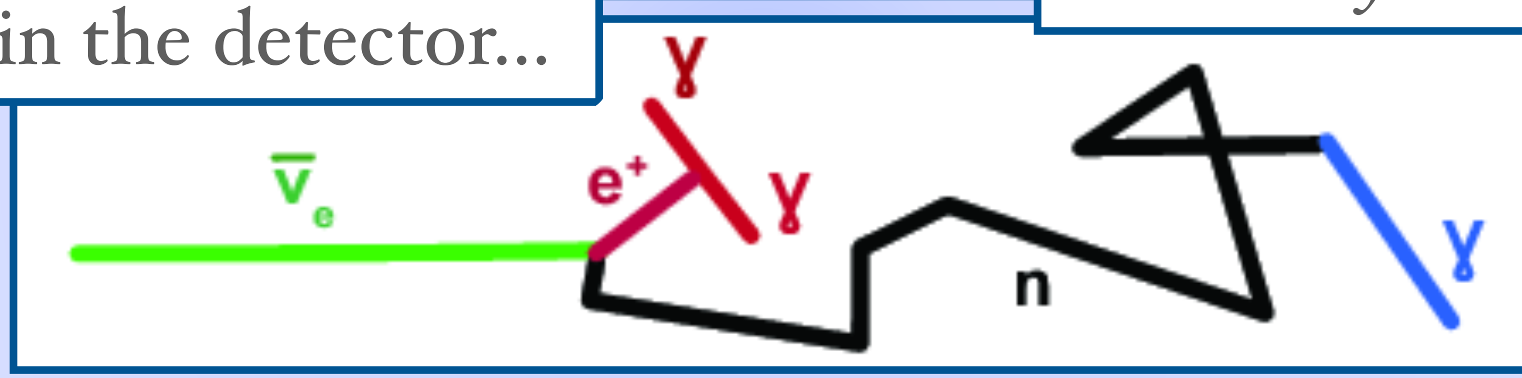
$p^+ \to e^+$

Positron goes off and *promptly* deposits energy in the detector…

…and the neutron is captured for a *delayed* energy deposition!



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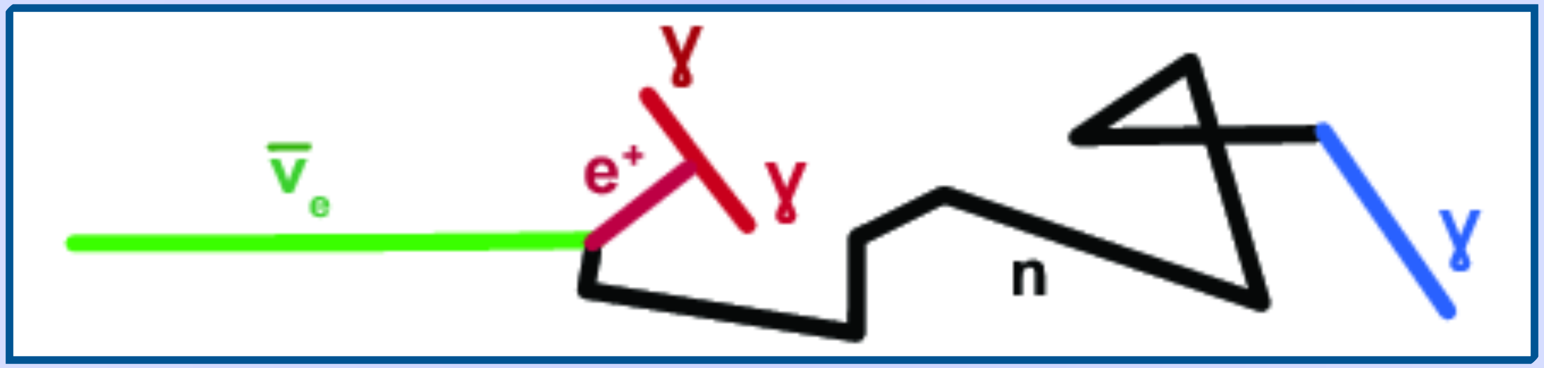

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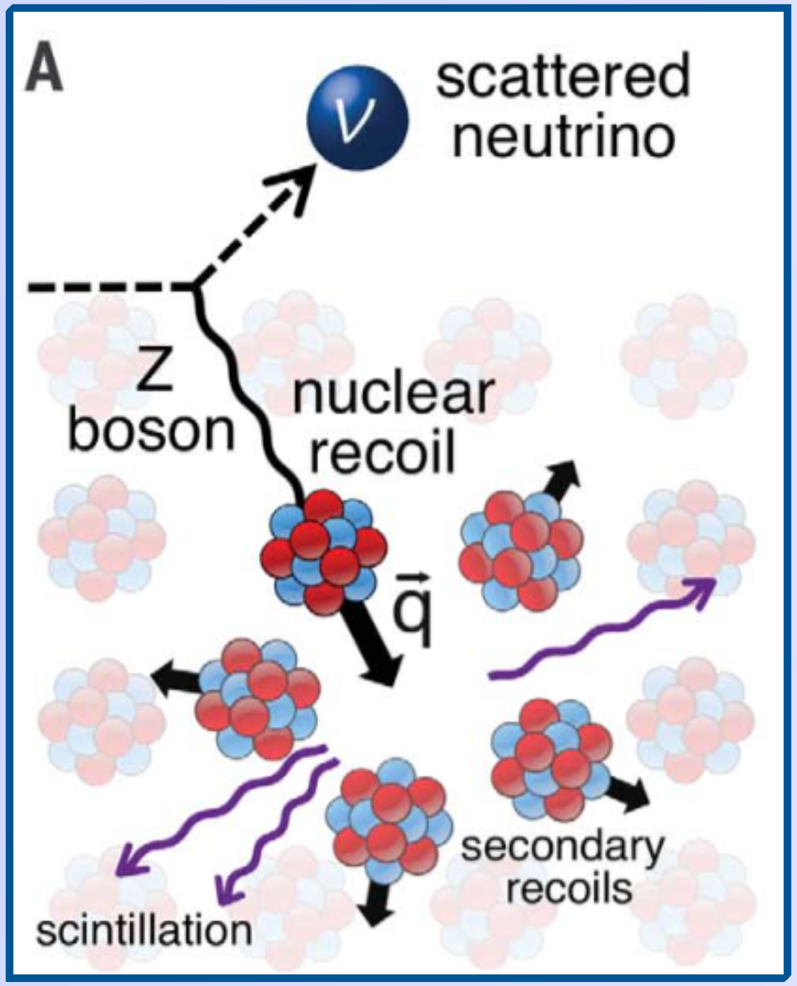
Detecting Reactor Antineutrinos

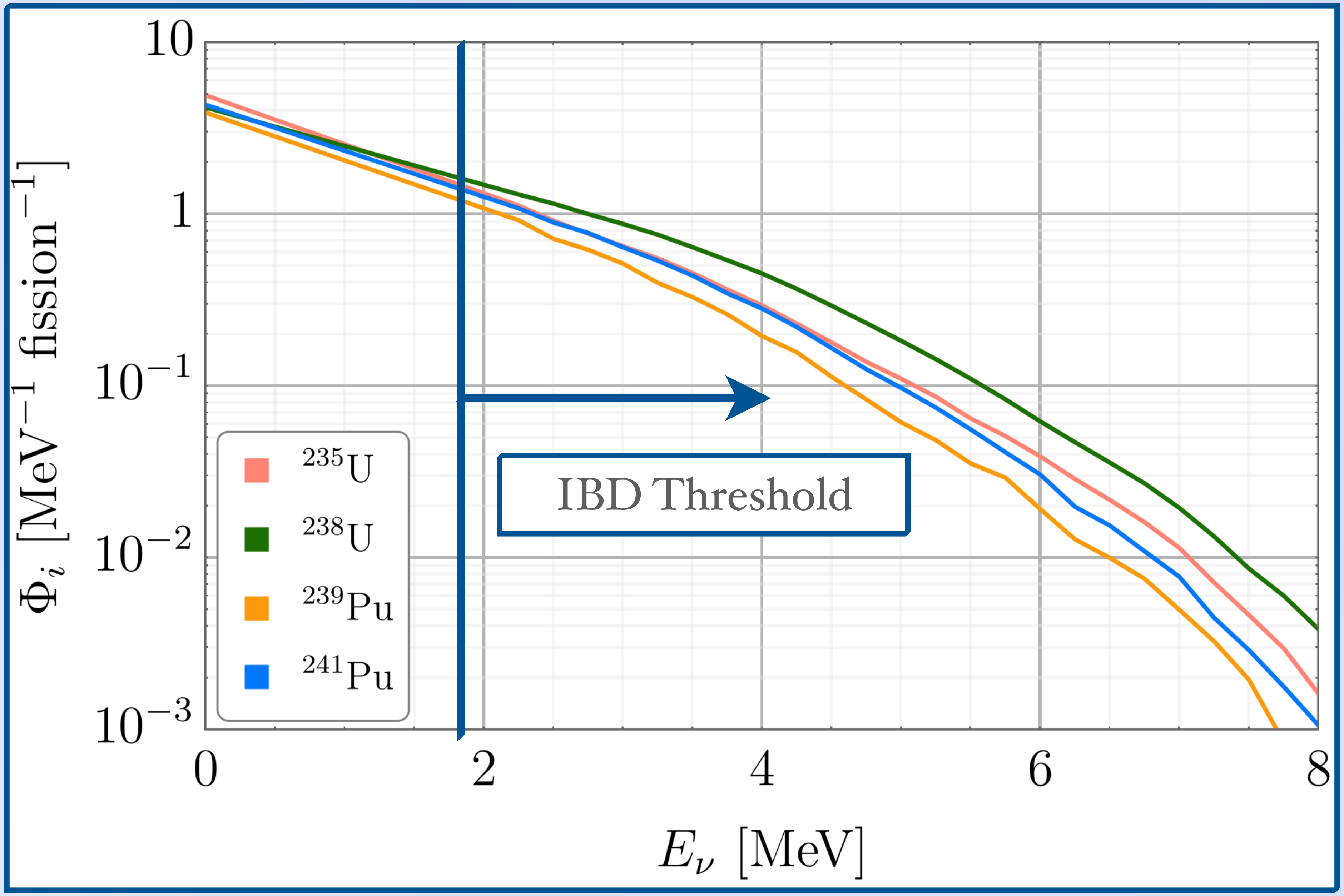
- New kid on the block: *Coherent Elastic Neutrino-Nucleus Scattering*, a.k.a., CEνNS:
  - Neutrino scatters off of *entire nucleus* instead of individual nucleons
  - Proposed to exist in 1974; discovered only in 2017



$$\frac{d\sigma_\alpha}{dE_\nu} = \frac{G_F^2}{2\pi} Q_\alpha^2 F^2(q^2) M_{(N,Z)} \left(2 - \frac{M_{(N,Z)} E_r}{E_\nu^2}\right)$$

D. Akimov, et al., Science 357 (2017) 1123

Antineutrinos from Reactors



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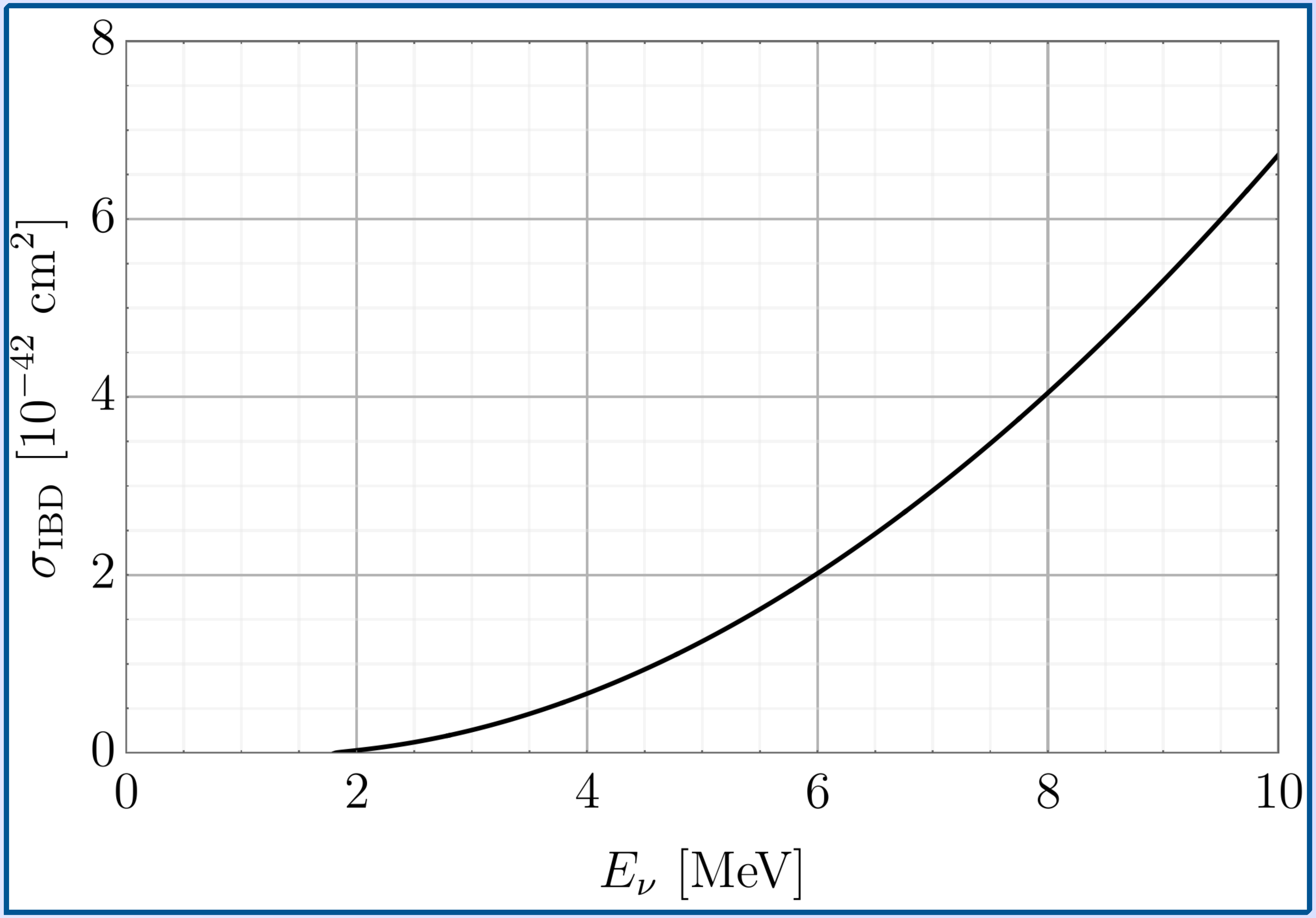

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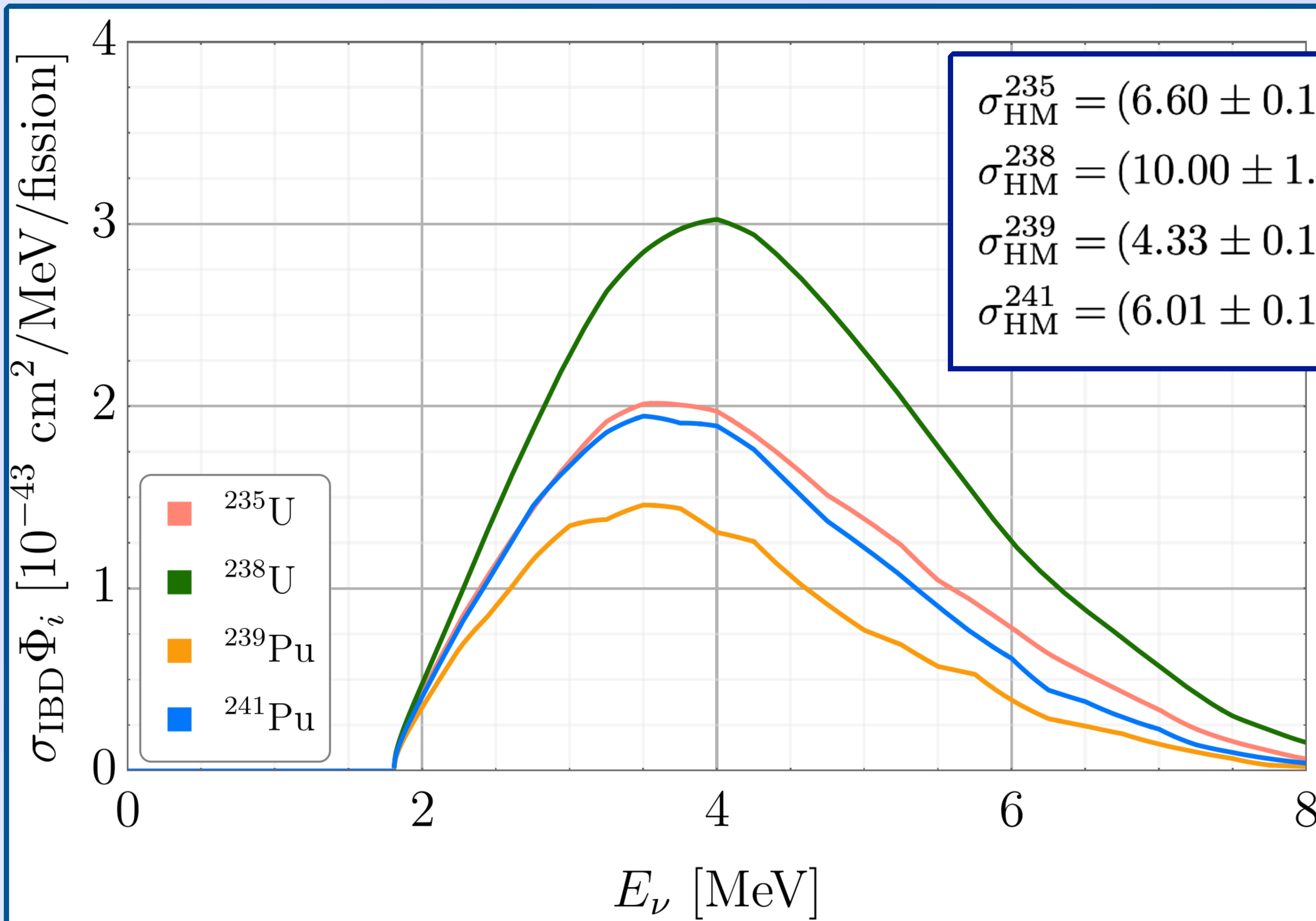

$$\sigma_{\mathrm{HM}}^{235} = (6.60 \pm 0.14) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{HM}}^{238} = (10.00 \pm 1.12) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{HM}}^{239} = (4.33 \pm 0.11) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{HM}}^{241} = (6.01 \pm 0.13) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$

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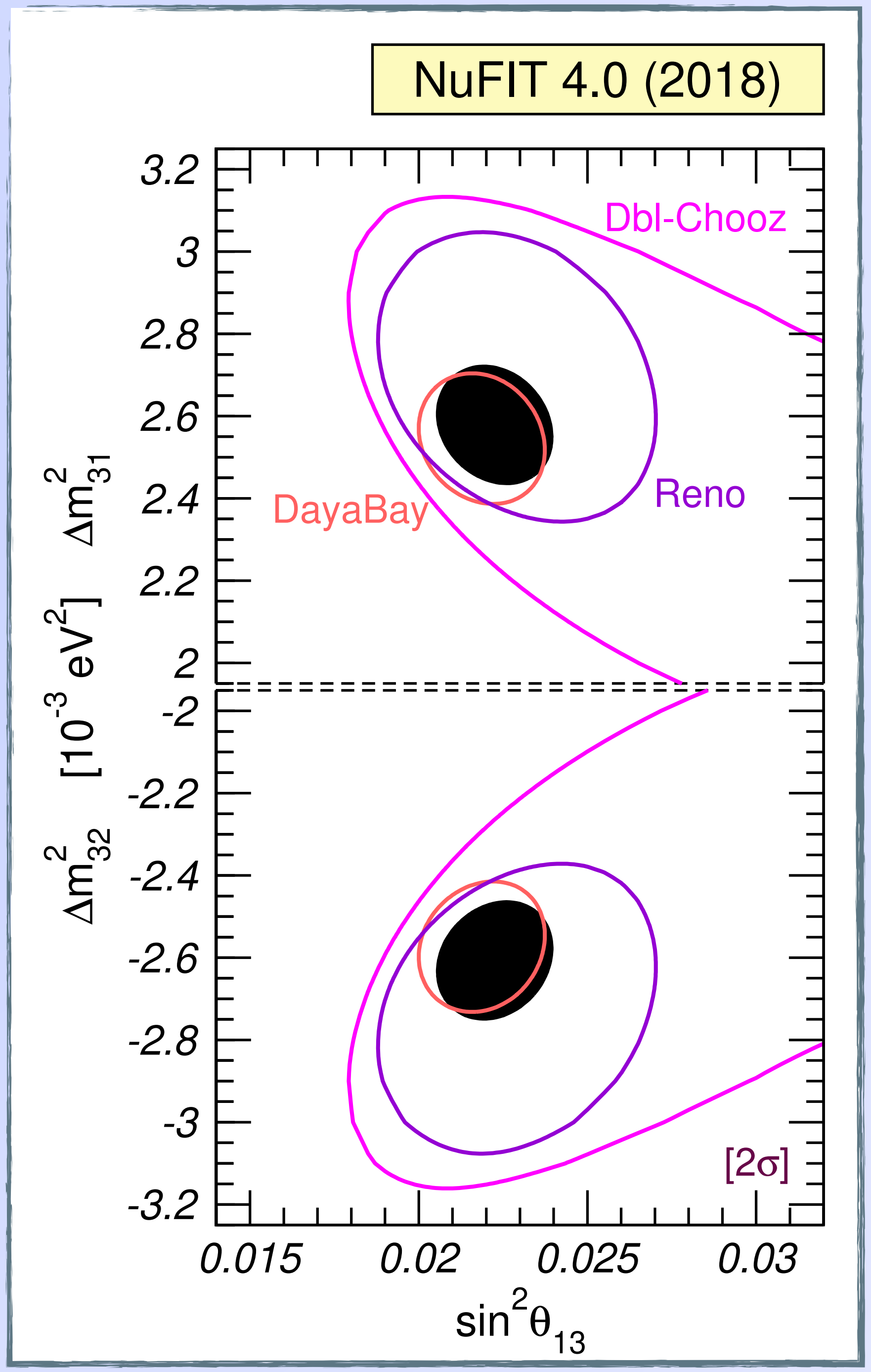
What Do Experiments See?

- Medium-baseline experiments (Daya Bay, RENO, Double Chooz) have measured θ_{13} to be *small* but *nonzero*
- KamLAND has measured the *solar* mixing parameters (θ_{12} & Δm^2_{21}) independently of solar experiments (*note the mild tension!*)



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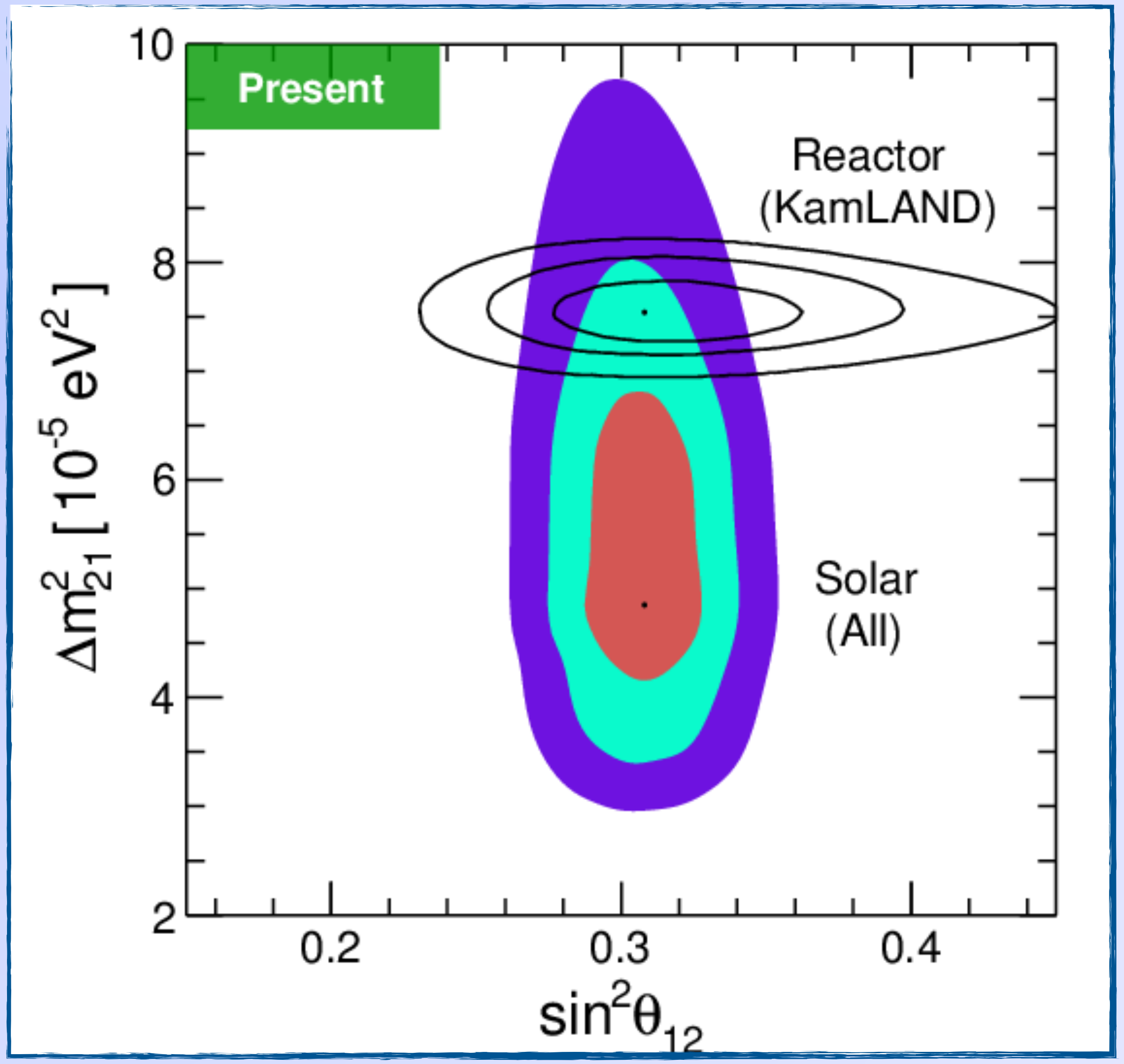

F. Capozzi, et al., PRL 123 (2019) 131803

What Do Experiments See?

a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	R^{exp}_a	σ^{exp}_a [%]	σ^{cor}_a [%]	σ^{the}_a [%]	L_a [m]
1	Bugey-4	0.538	0.078	0.328	0.056	0.932	1.4	1.4	2.5	15
2	Rovno91	0.606	0.074	0.277	0.043	0.930	2.8		2.4	18
3	Rovno88-1I	0.607	0.074	0.277	0.042	0.907	6.4	3.1	2.4	18
4	Rovno88-2I	0.603	0.076	0.276	0.045	0.938	6.4		2.4	18
5	Rovno88-1S	0.606	0.074	0.277	0.043	0.962	7.3	2.2	2.4	18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3	3.1	2.5	25
7	Rovno88-2S	0.606	0.074	0.274	0.046	0.928	6.8		2.4	18
8	Bugey-3-15	0.538	0.078	0.328	0.056	0.936	4.2		2.5	15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3	4.0	2.5	40
10	Bugey-3-95	0.538	0.078	0.328	0.056	0.867	15.2		2.5	95
11	Gosgen-38	0.619	0.067	0.272	0.042	0.955	5.4		2.4	37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4	2.0	2.4	45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7	3.8	2.4	64.7
14	ILL	1	0	0	0	0.792	9.1		2.4	8.76
15	Krasnoyarsk87-33	1	0	0	0	0.925	5.0	4.1	2.4	32.8
16	Krasnoyarsk87-92	1	0	0	0	0.942	20.4		2.4	92.3
17	Krasnoyarsk94-57	1	0	0	0	0.936	4.2	0	2.4	57
18	Krasnoyarsk99-34	1	0	0	0	0.946	3.0	0	2.4	34
19	SRP-18	1	0	0	0	0.941	2.8	0	2.4	18.2
20	SRP-24	1	0	0	0	1.006	2.9	0	2.4	23.8
21	Nucifer	0.926	0.061	0.008	0.005	1.014	10.7	0	2.3	7.2
22	Chooz	0.496	0.087	0.351	0.066	0.996	3.2	0	2.5	≈ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0	2.4	≈ 800
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0	2.5	≈ 550
25	RENO	0.569	0.073	0.301	0.056	0.944	2.2	0	2.4	≈ 411
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0	2.5	≈ 415

S. Gariazzo, et al., JHEP 1706 (2017) 135

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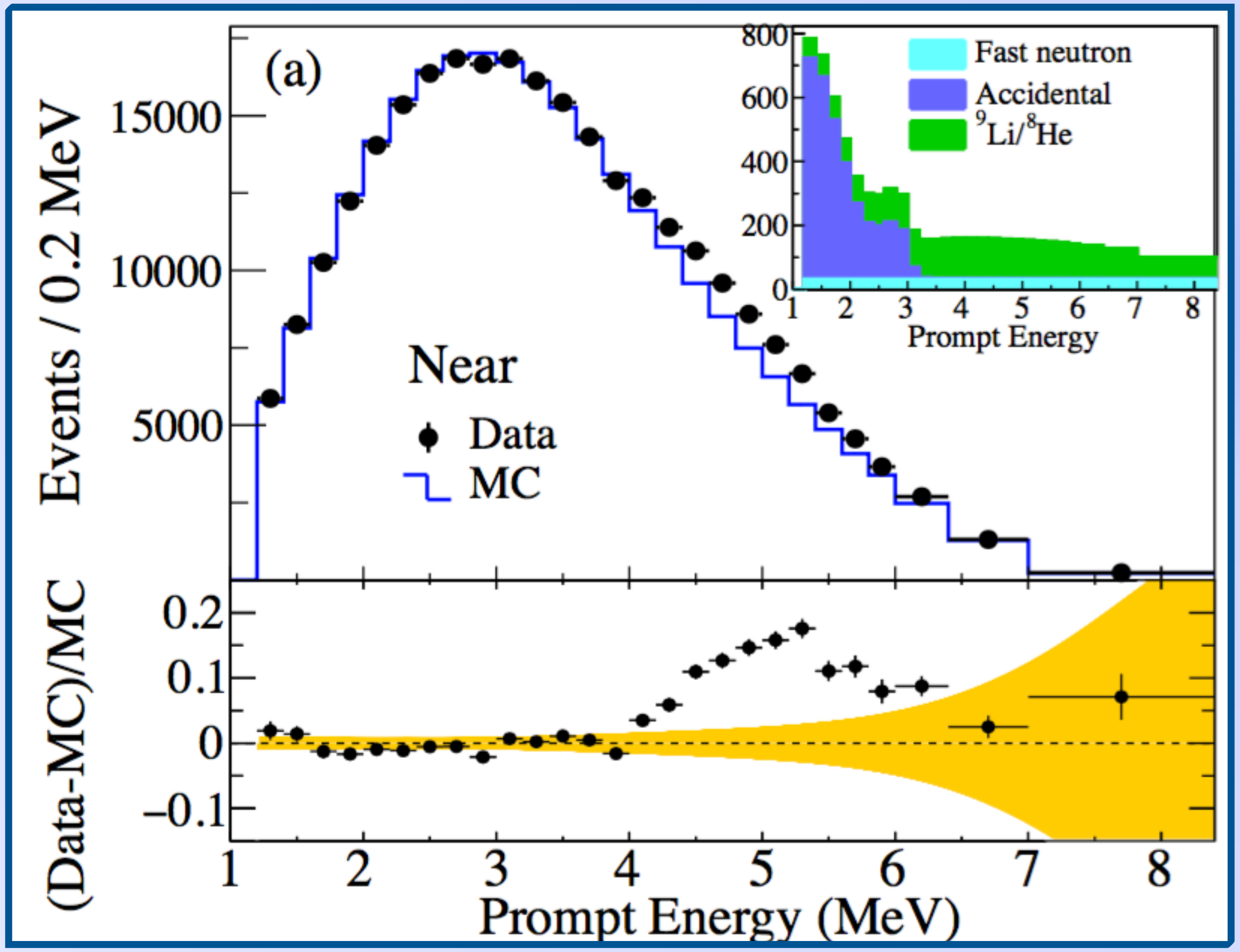
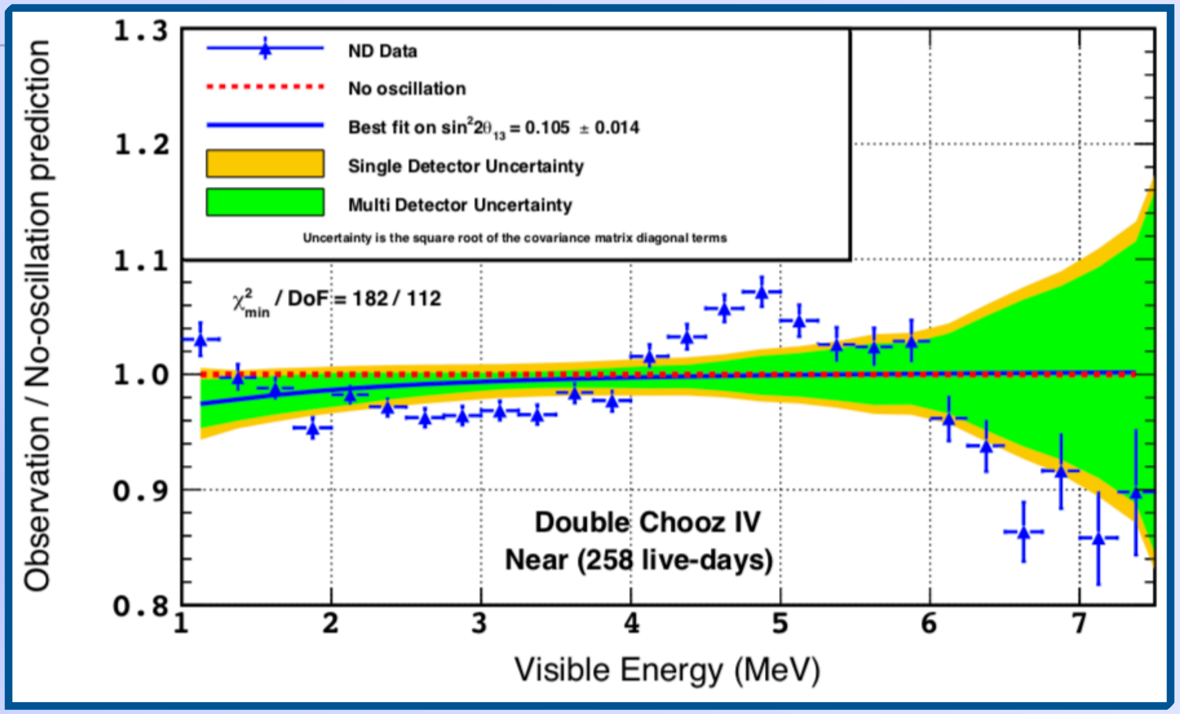
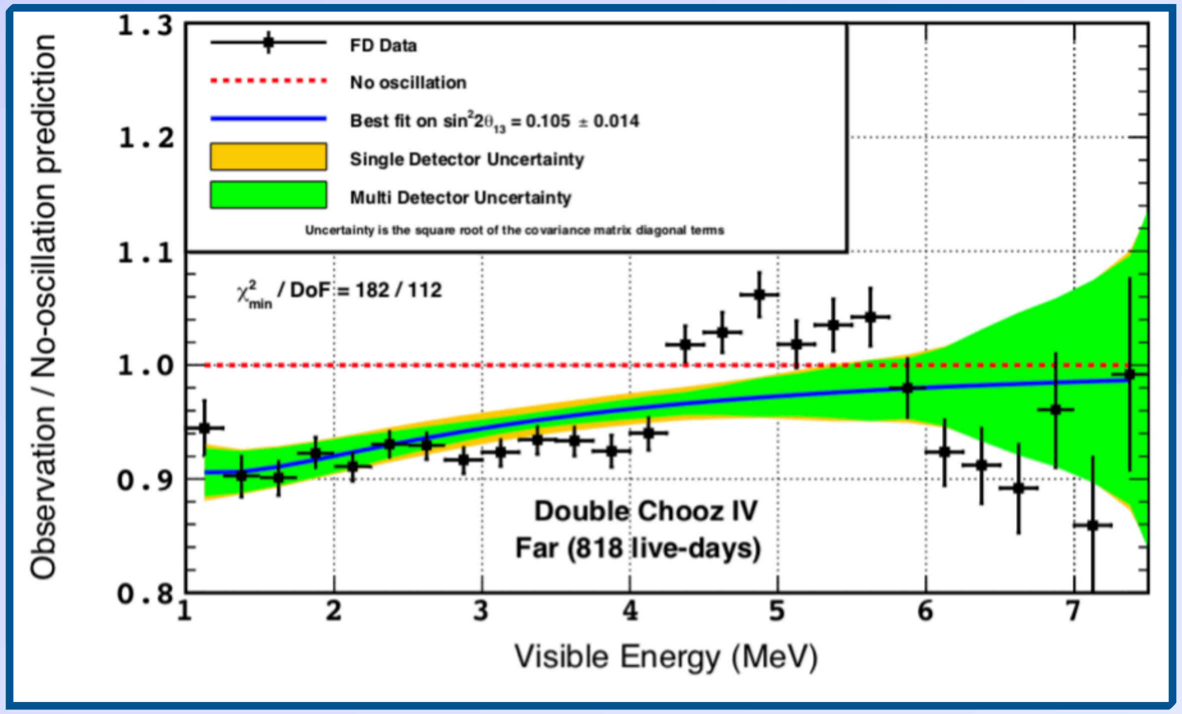
Short-baseline experiments almost always find fewer antineutrinos than expected!

S. Gariazzo, et al., *JHEP* 1706 (2017) 135

The 5 MeV Bump







RENO Collaboration, PRD 98 (2018) 012002; Double Chooz Collaboration, Nature Phys. 16 (2020) 558; Daya Bay Collaboration, PRL 123 (2019) 111801; NEOS Collaboration, PRL 118 (2017) 121802

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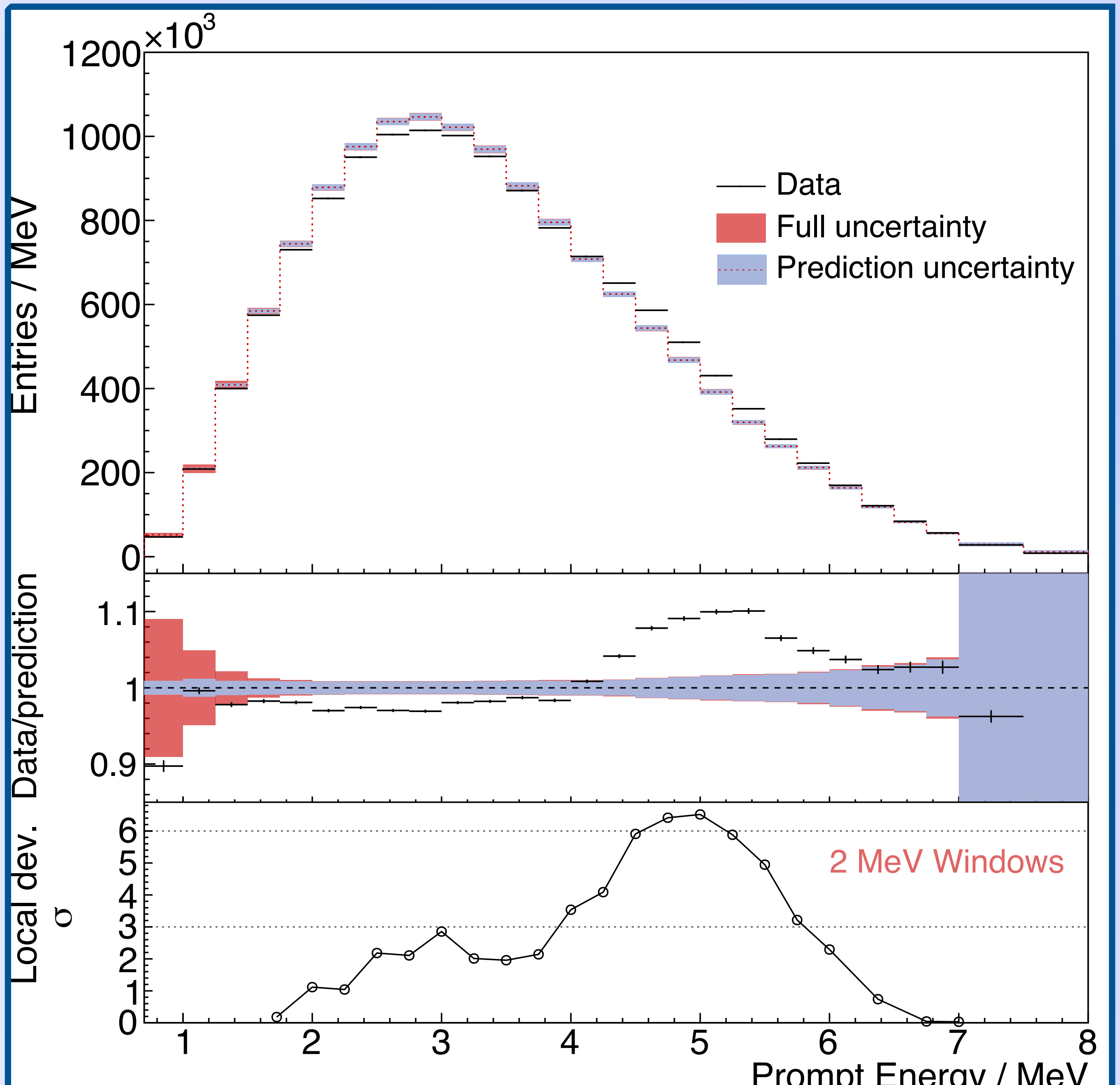

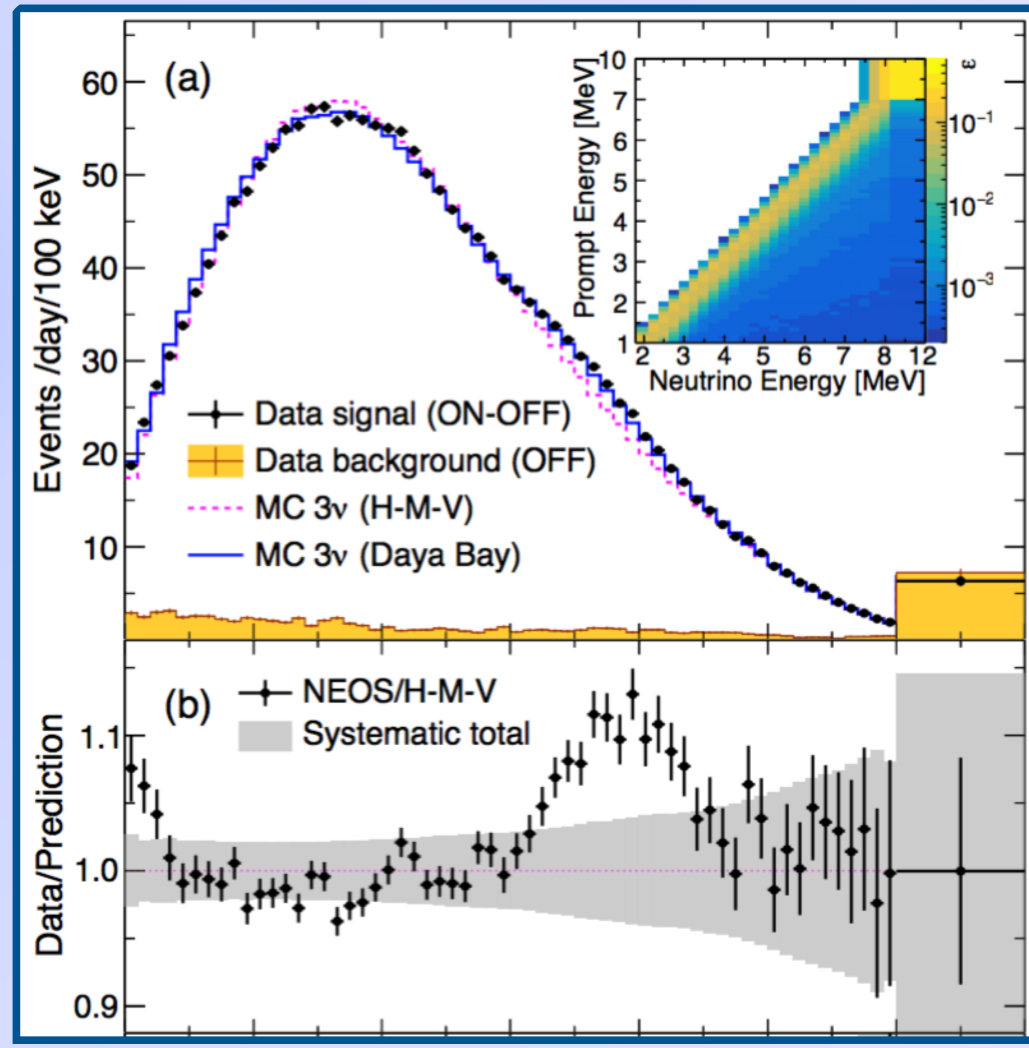

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Causes of the Anomalies?

- Possible explanations:
  - Oscillations with four (or more?) neutrinos
  - Reactor fluxes need to be reevaluated
    - Normalizations?
    - Shapes?
  - Other new physics?
    - We looked into this – *probably not* the case…

Data	Analysis	Best fit ($\sin^2 2\theta_{14}$, Δm^2_{41})	$\chi^2_{\rm min}$/dof	$\Delta\chi^2$(no osc.)	p-value/$\#\sigma$ (no osc.)
React-old	flux-fixed	(0.12, 1.72)	52.1/68	9.4	0.0091/2.6σ
React-old	flux-free	(0.06, 0.46)	51.6/66	2.8	0.25/1.2σ
React-all	flux-fixed	(0.12, 2.99)	196.0/236	11.3	0.0036/2.9σ
React-all	flux-free	(0.04, 1.72)	187.5/234	5.6	0.061/1.9σ
Global	flux-fixed	(0.06, 1.72)	554.3/594	11.9	0.0026/3.0σ
Global	flux-free	(0.04, 1.72)	545.2/592	7.0	0.031/2.2σ

M. Dentler, et al., JHEP 11 (2017) 099

Analysis	Δm^2_{41} [eV^2]	$\lvert U^2_{e4}\rvert$	$\chi^2_{\rm min}$/dof	$\Delta\chi^2$(no-osc)	significance
DANSS+NEOS	1.3	0.00964	74.4/(84 − 2)	13.6	3.3σ
all reactor (flux-free)	1.3	0.00887	185.8/(233 − 5)	11.5	2.9σ
all reactor (flux-fixed)	1.3	0.00964	196.0/(233 − 3)	15.5	3.5σ
$\overset{(-)}{\nu}_e$ disap. (flux-free)	1.3	0.00901	542.9/(594 − 8)	13.4	3.2σ
$\overset{(-)}{\nu}_e$ disap. (flux-fixed)	1.3	0.0102	552.8/(594 − 6)	17.5	3.8σ

M. Dentler, et al., JHEP 08 (2018) 010

JMB, V. Brdar, P. Huber, PRD 99 (2019) 055045

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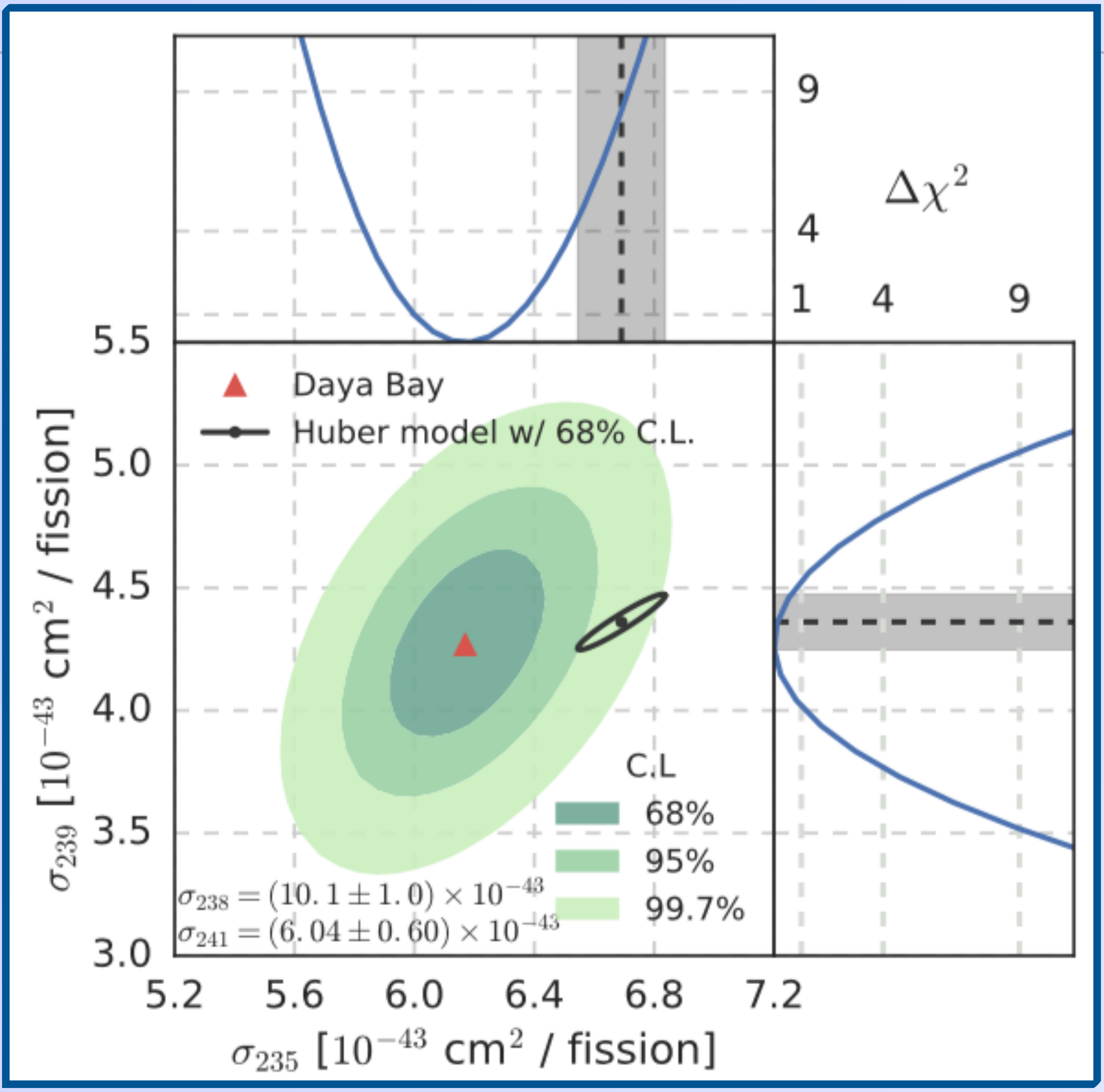


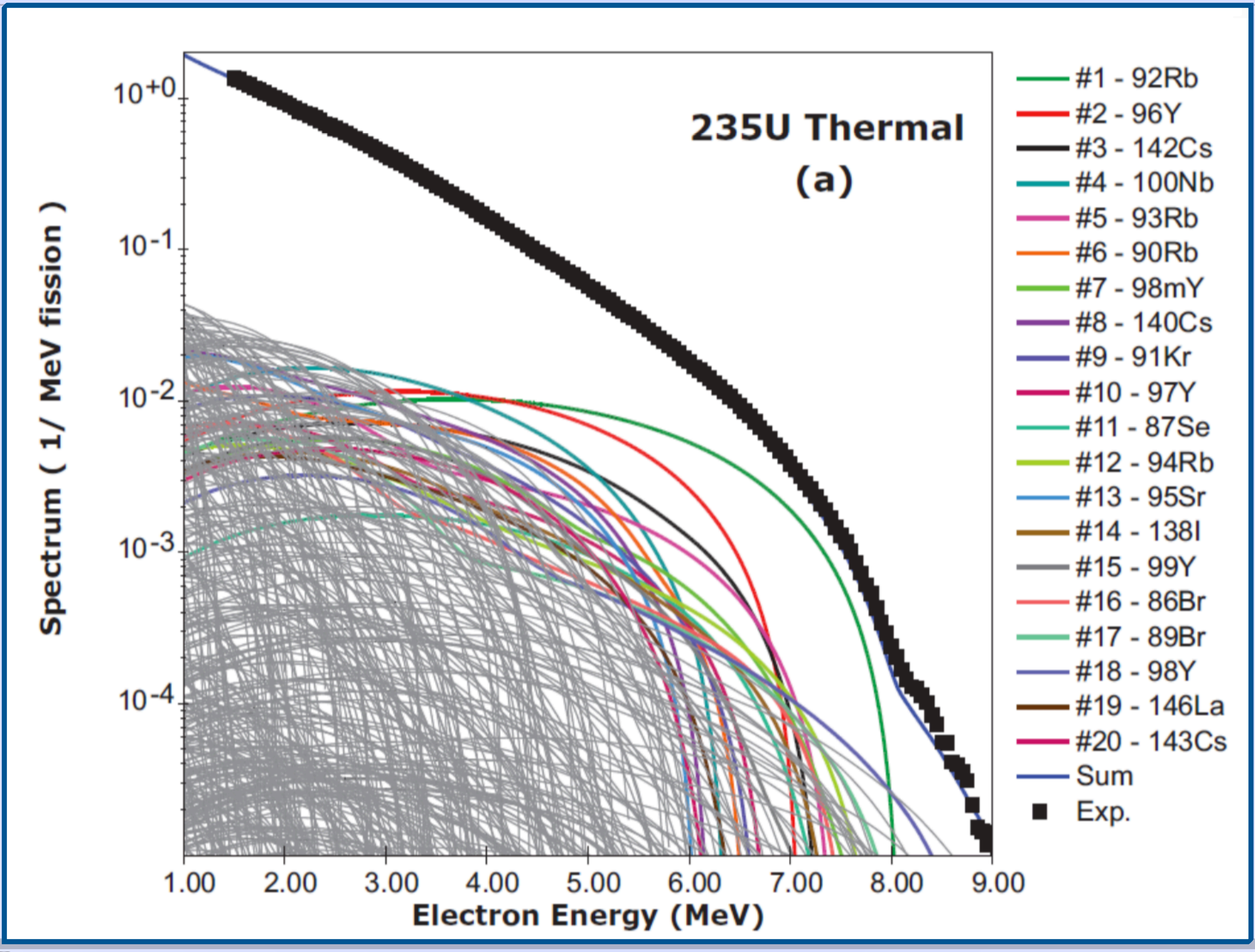
Daya Bay Collaboration, PRL 118 (2017) 251801

Analysis	$\chi^2_{\rm min}$/dof	gof	$\sin^2 2\theta_{14}^{\rm bfp}$	$\Delta\chi^2$(no osc)
fixed fluxes + ν_s	9.8/(8 − 1)	18%	0.11	3.9
free fluxes (no ν_s)	3.6/(8 − 2)	73%		

M. Dentler, et al., JHEP 11 (2017) 099

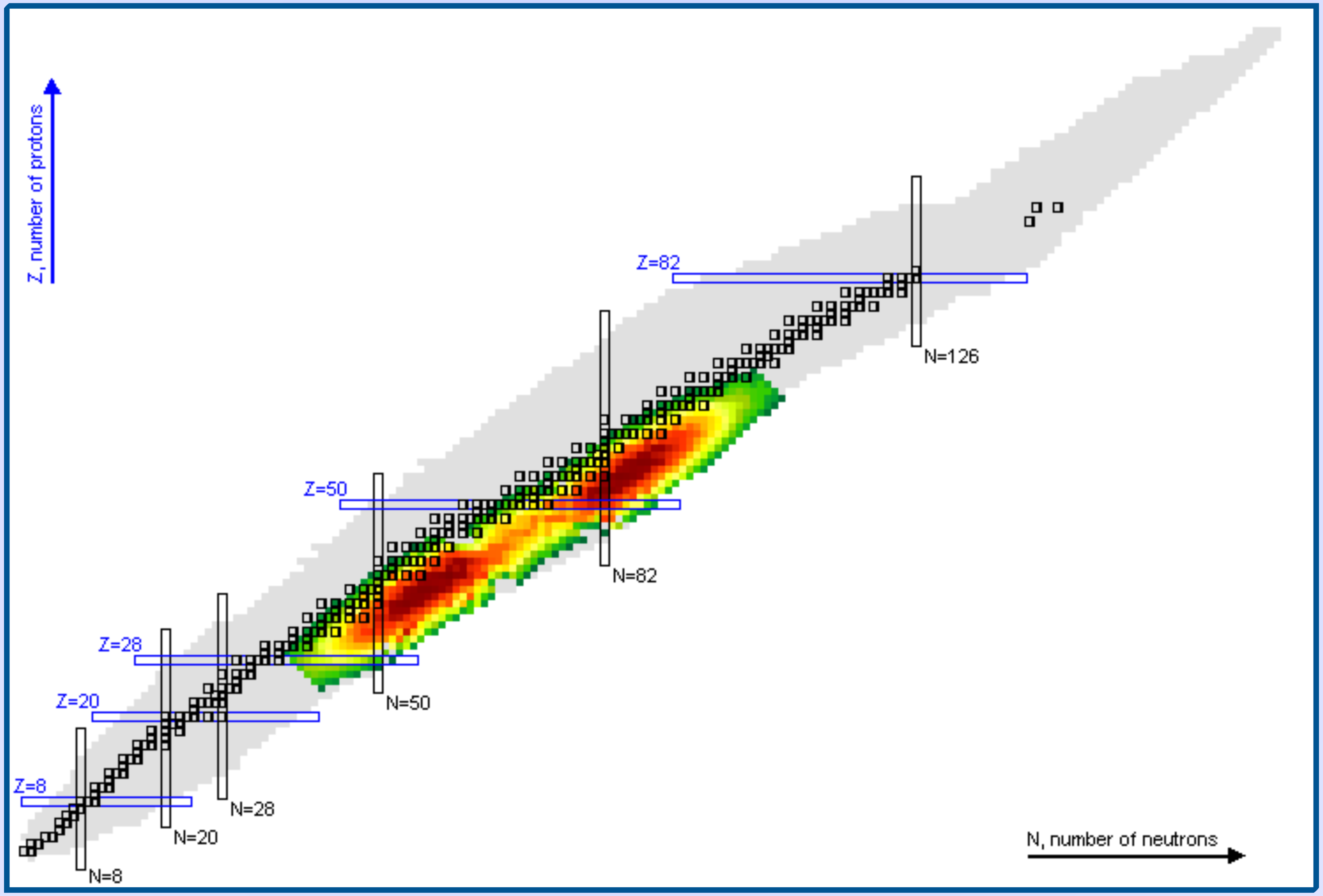
JMB, V. Brdar, P. Huber, PRD 99 (2019) 055045

Ab Initio Method



Ab Initio Method

Ingredient 1: (Cumulative) Fission Yields



Fission yields from ^{235}U from www.nndc.bnl.gov/nudat2;
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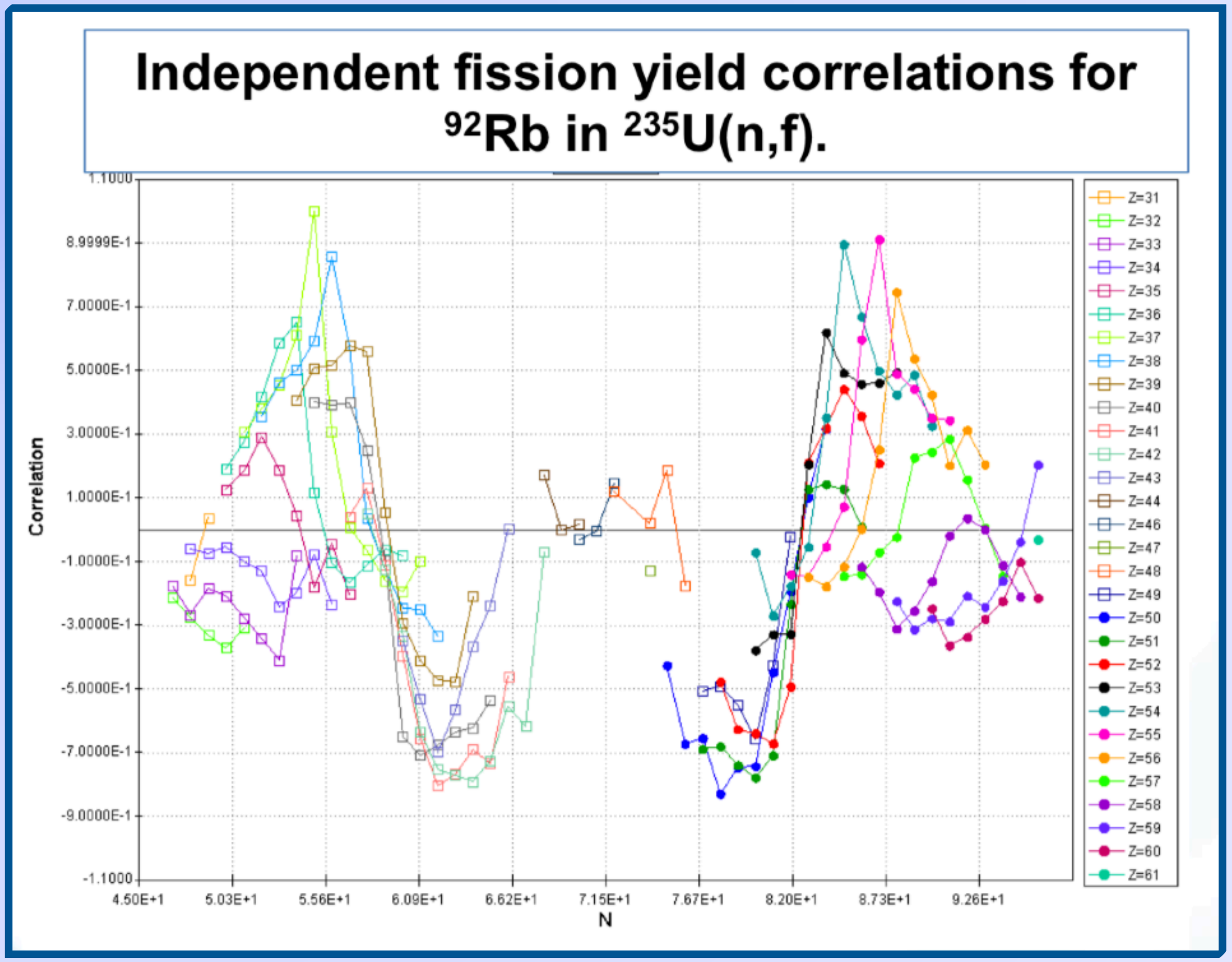
However, not just uncertainties, but *correlations*!

These correlations have previously not been taken into account in *databases* – and thus in *predictions*!



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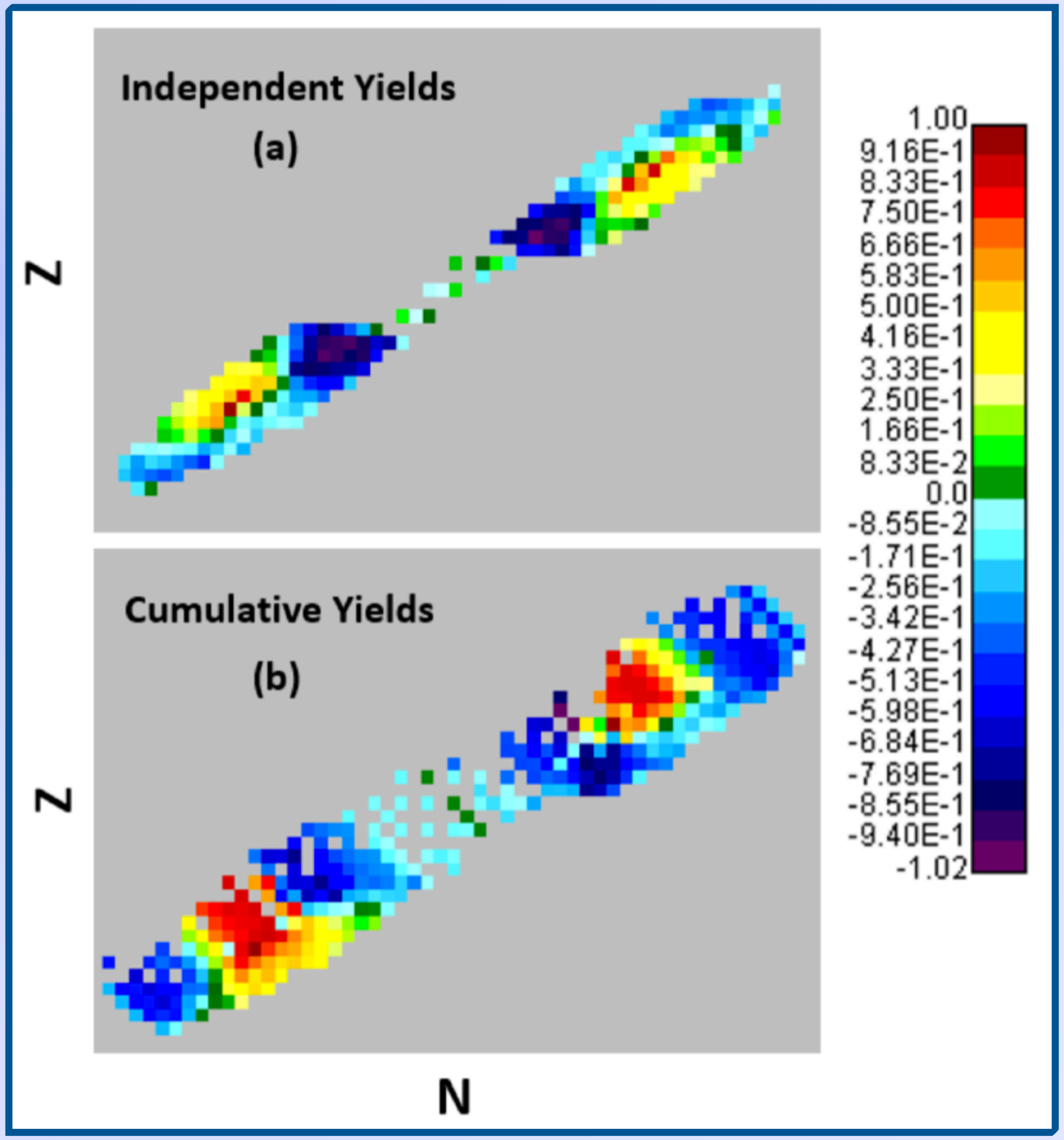

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Ab Initio Method

Ingredient 2: Beta-Decay Spectra

Need to understand relative beta decay strengths of each fission product and their spectra.

Two important systematics:

1. Measurements using HPGe detectors are subject to *pandemonium effect*
2. Nuclear properties of the transition determines *shape* of energy spectrum

V. Guadilla, et al., PRC 100 (2019) 044305

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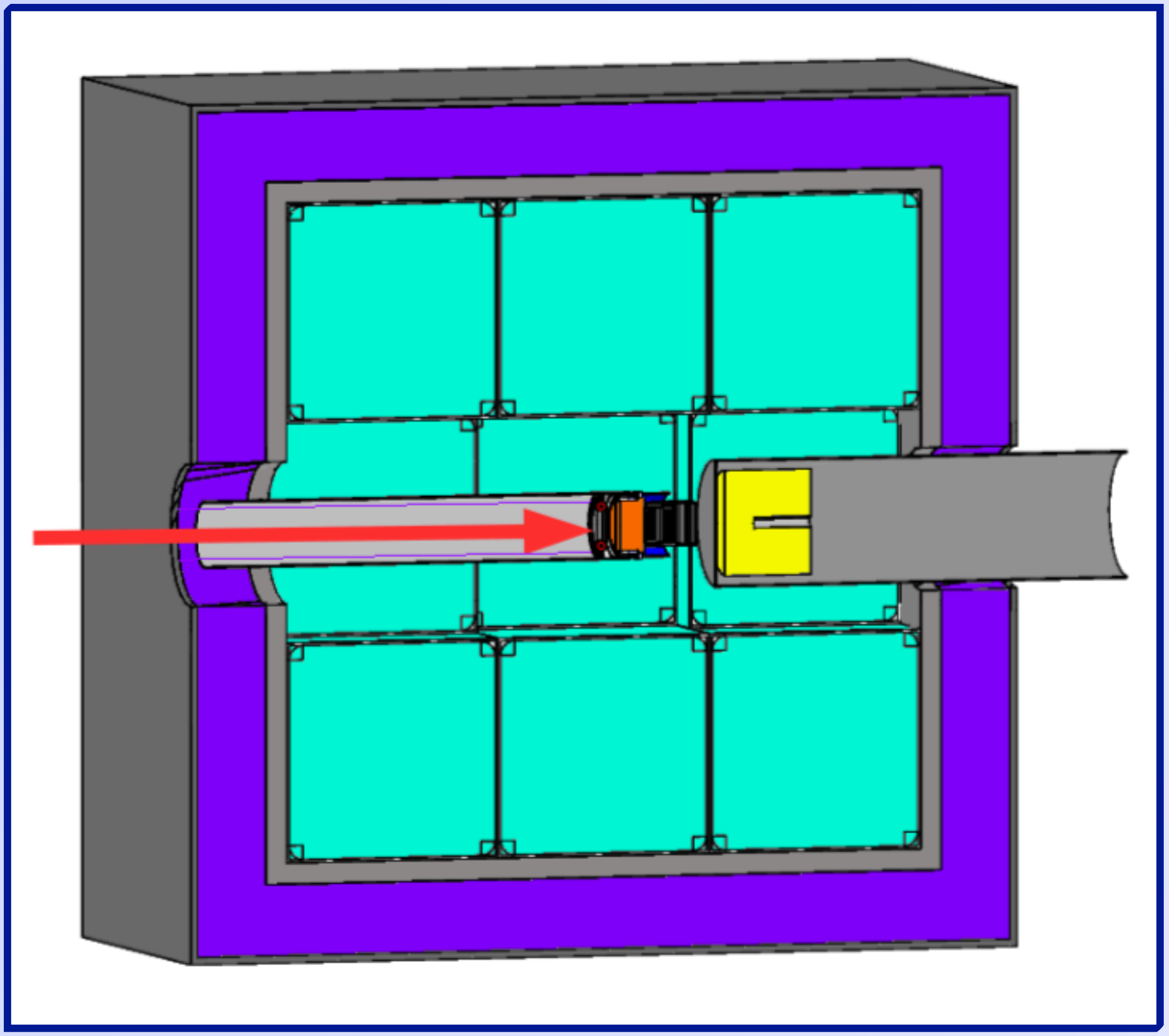

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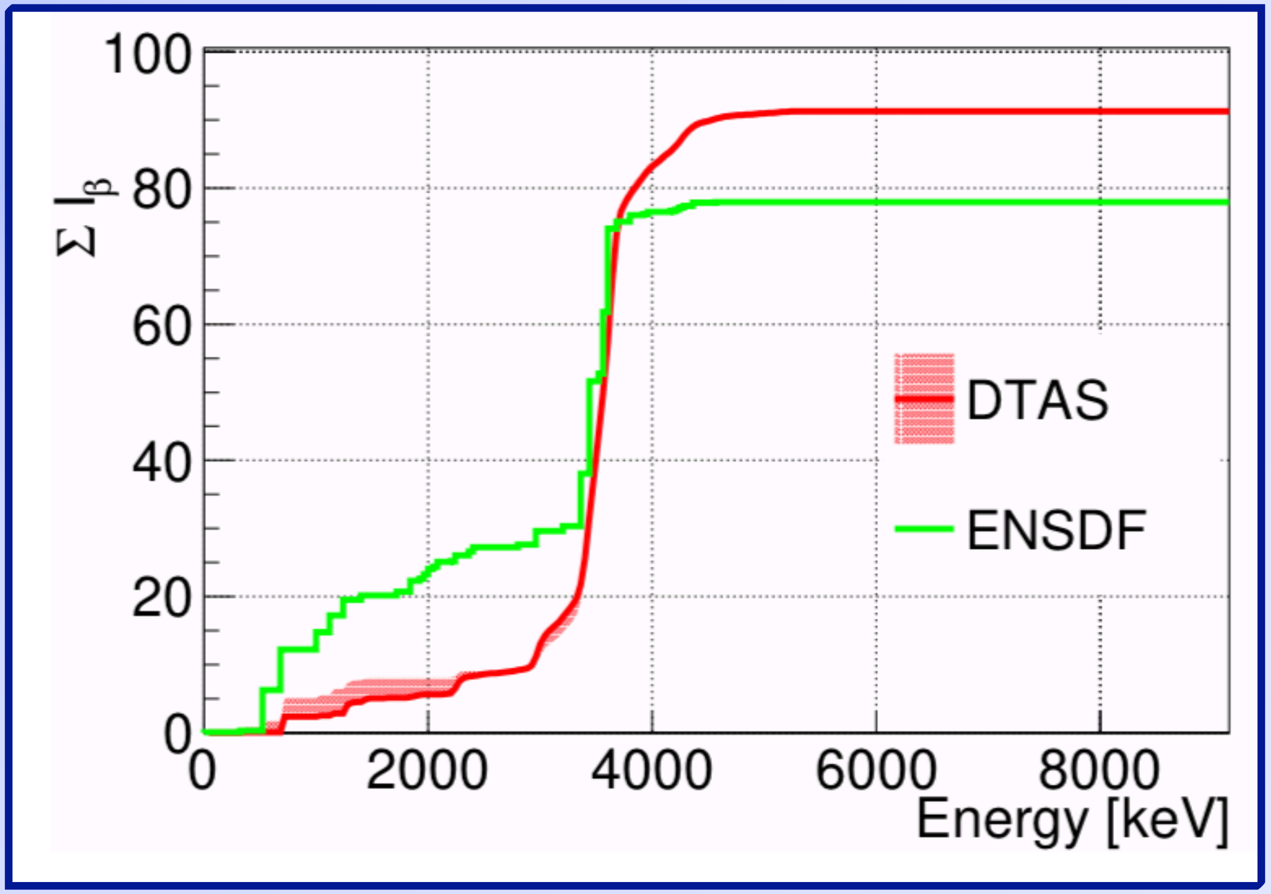

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Conversion Method

The aggregate beta spectrum is given by

$$\boxed{\begin{array}{c} S_e(E) = \sum_i a_i S_i(E,\, E_0^i) \\ S_i(E,\, E_0^i) = p_e E_e \left(E_0^i - E_e\right)^2 C(E_e) F(E_e, Z_{\text{eff}}) \left(1 + \delta_{\text{corrections}}\right) \end{array}}$$

The messy parts are:

- *$C(E_e)$ – The Shape Factor*
  - This function is unity for *allowed* transitions, but is nontrivial for anything more complicated than this!
- *$\delta_{\text{corrections}}$ – Higher-order corrections*
  - Includes (energy-dependent) corrections, which may be different for electrons and antineutrinos
  - Some are well known; others are not (e.g., *weak magnetism*)

The antineutrino spectrum requires the replacement $E_e \to E_0^i - E_e$

Th. A. Mueller, et al., PCR 83 (2011) 054615; P. Huber, PRC 84 (2011) 024617 (Erratum: PRC 85 (2012) 029901); L. Hayen, et al., PRC 99 (2019) 031301, PRC 100 (2019) 054323 ; X. Wang @ AAP 2019

Conversion Method

Measure S_e; find some way to determine these!

The aggregate beta spectrum is given by

$$S_e(E) = \sum_i a_i S_i(E,\, E_0^i)$$

$$S_i(E,\, E_0^i) = p_e E_e \left(E_0^i - E_e\right)^2 C(E_e) F(E_e, Z_{\text{eff}}) \left(1 + \delta_{\text{corrections}}\right)$$

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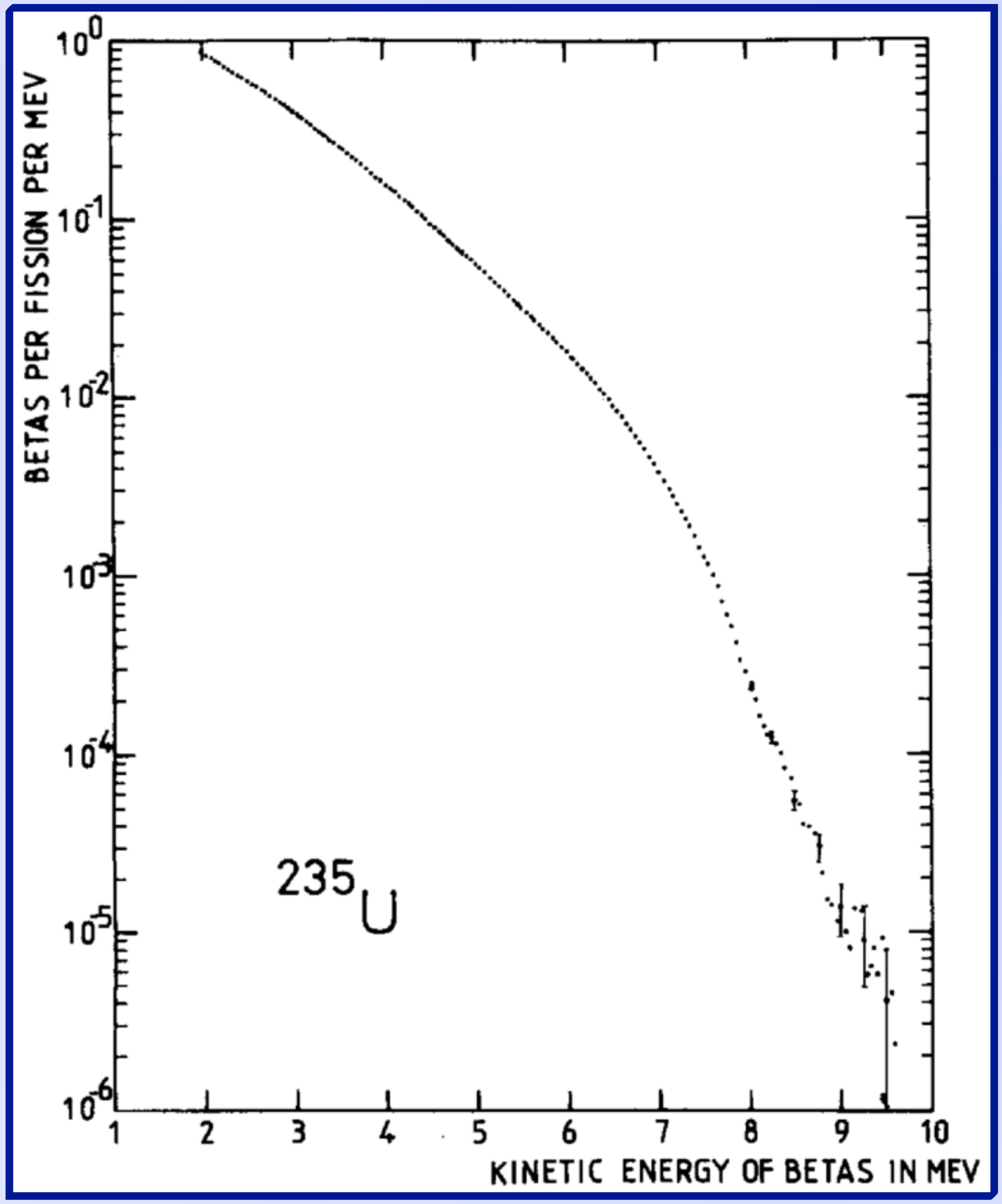
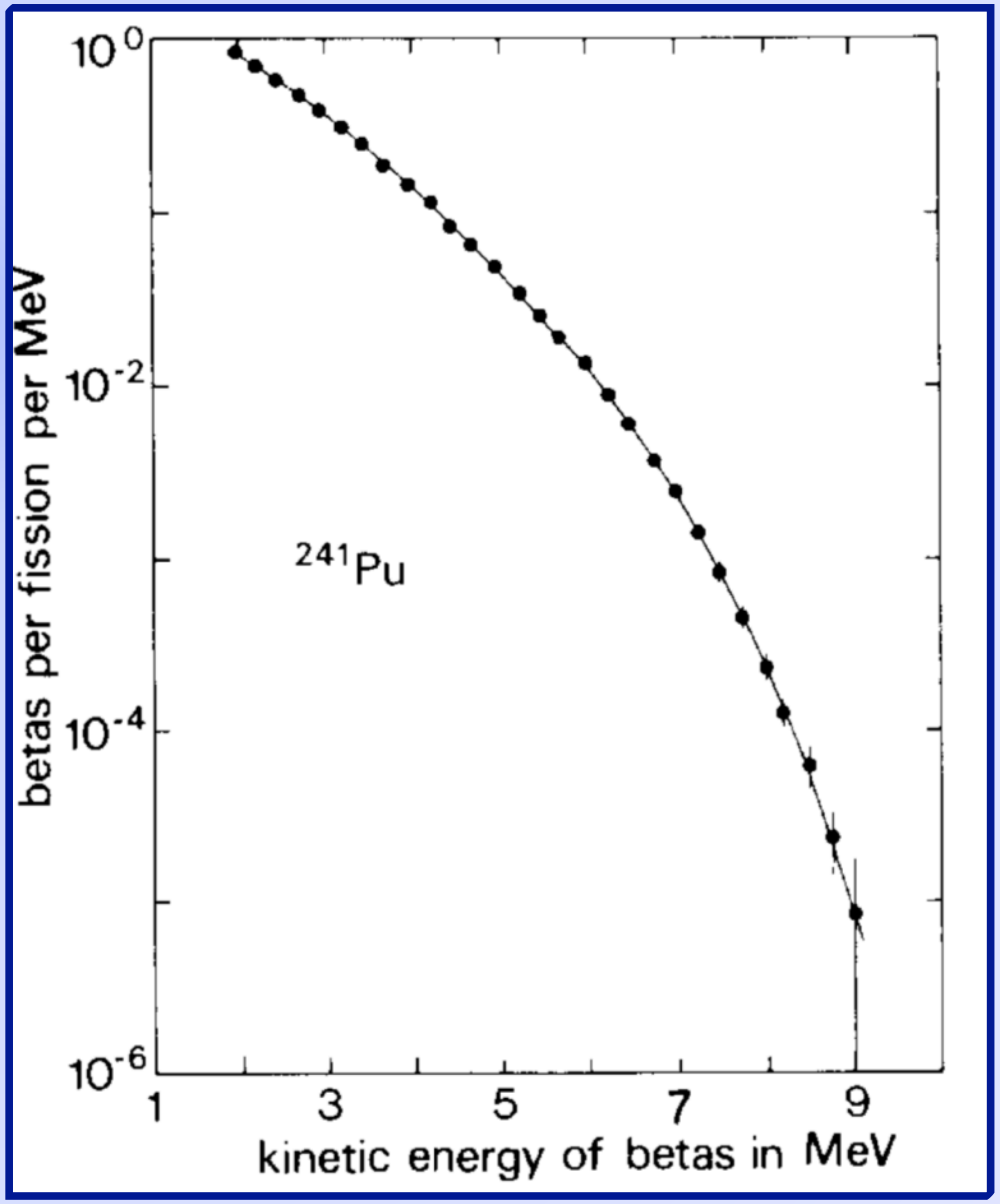
Conversion Method

Ingredient 1: Measured Aggregate Beta Spectra





K. Schreckenbach, et al., PL 160B (1985) 325;
A. A. Hahn, et al., PLB 218 (1989) 365

Conversion Method

Ingredient 2: Spectral Inversion

The *actual* beta endpoints are unknown – use the technique of *virtual branches:*

- Take some set of beta-spectrum data points from the end of the energy spectrum
- Fit these data to a *fictitious* transition; extend to low energies and subtract that from the remaining electron data
- Repeat!

Important subtleties:

- HM assume these transitions to be of allowed type – this is an incredibly important assumption!
- The value of Z_{eff} used is the average Z value for isotopes that contribute a decay in that energy window

Part 2: Wrangling the Data

Developing a Global Fit

- The idea is fairly simple: combine all experimental results together, accounting for, e.g., correlations. This is nothing new!
- However, develop it in **`GLoBES`** & allow for it to be widely distributed:

1. Let people make *informed criticisms* of the analyses.
2. Allow for *modifications*: test your own NP scenario, use a new flux model, update cross sections, etc.

- The code (**`GLoBESfit`**) is now available at www.globesfit.org – feel free to poke around!

Experimental Data Set(s)

Two types of measurements:

- *Rate measurements*:
  - *Integrated Rate*: Bugey(-3 & -4); Chooz; Double Chooz; Gösgen; ILL; Krasnoyarsk ('87, '94, '99); Nucifer; Palo Verde; Rovno ('88 & '91); Savannah River
  - *Rate Evolution*: Daya Bay, RENO
  - Total: 40 Data Points
- *Spectrum measurements*: Bugey-3; DANSS; Daya Bay; Double Chooz; NEOS; RENO
  - Total: 212 Data Points

Analyzing Rates

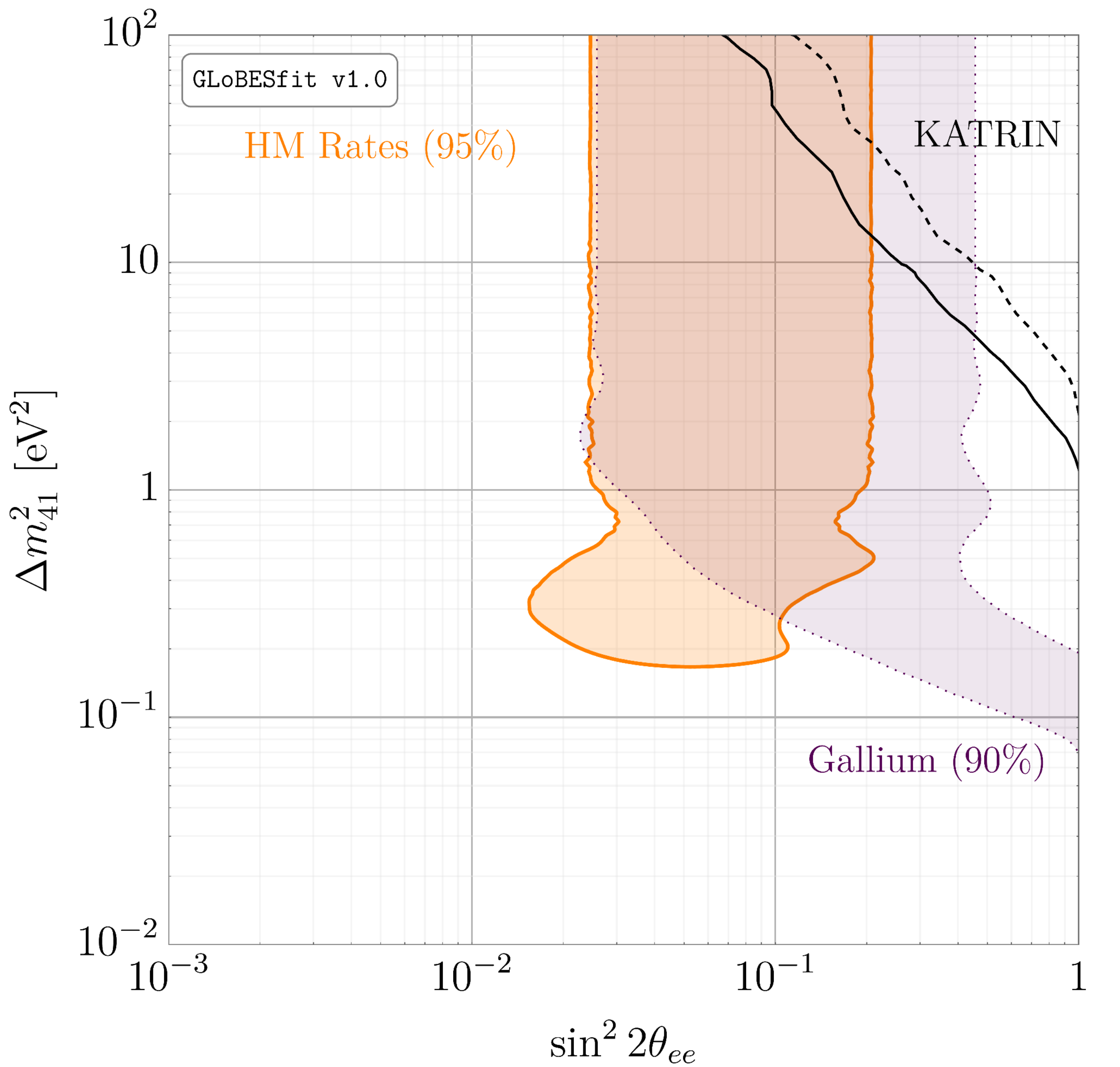
The gist of the analysis:

1. Calculate 4ν/no-osc. ratio $\vec{R}_{\rm pred}$ over parameter space:
   a. Energy resolution, fuel fractions, etc., all accounted for.
2. Recalculate the experimentally measured ratios $\vec{R}_{\rm exp}$:
   a. These are calculated from the *original papers.*
3. Accounting for *correlations*, calculate:

$$\boxed{\begin{aligned}\chi^2 = \quad & (\vec{R}_{\rm exp} - \vec{R}_{\rm pred})^T \cdot V_{\rm exp}^{-1} \cdot (\vec{R}_{\rm exp} - \vec{R}_{\rm pred}) \\ & + \vec{\xi}^T \cdot V_{\rm th}^{-1} \cdot \vec{\xi},\end{aligned}}$$

JMB & P. Huber, PRD 101 (2020) 015008; arXiv:2005.01756

HM Rate Analysis



$$P_{ee}^{2\nu} = 1 - \sin^2 2\theta_{ee} \sin^2 \left(\frac{\Delta m^2_{41} L}{4E_\nu} \right)$$

- This is consistent with previous analyses:
  - *M. Dentler, et al., JHEP 08 (2018) 010*
  - *C. Giunti, et al., PRD 99 (2019) 073005*
- For context, also showing recent reevaluation of the gallium anomaly
- Total significance: 2.5σ

J. Kostensalo, et al., PLB 795 (2019) 542; C. Giunti, et al., JHEP 05 (2020) 061;

New Flux Predictions

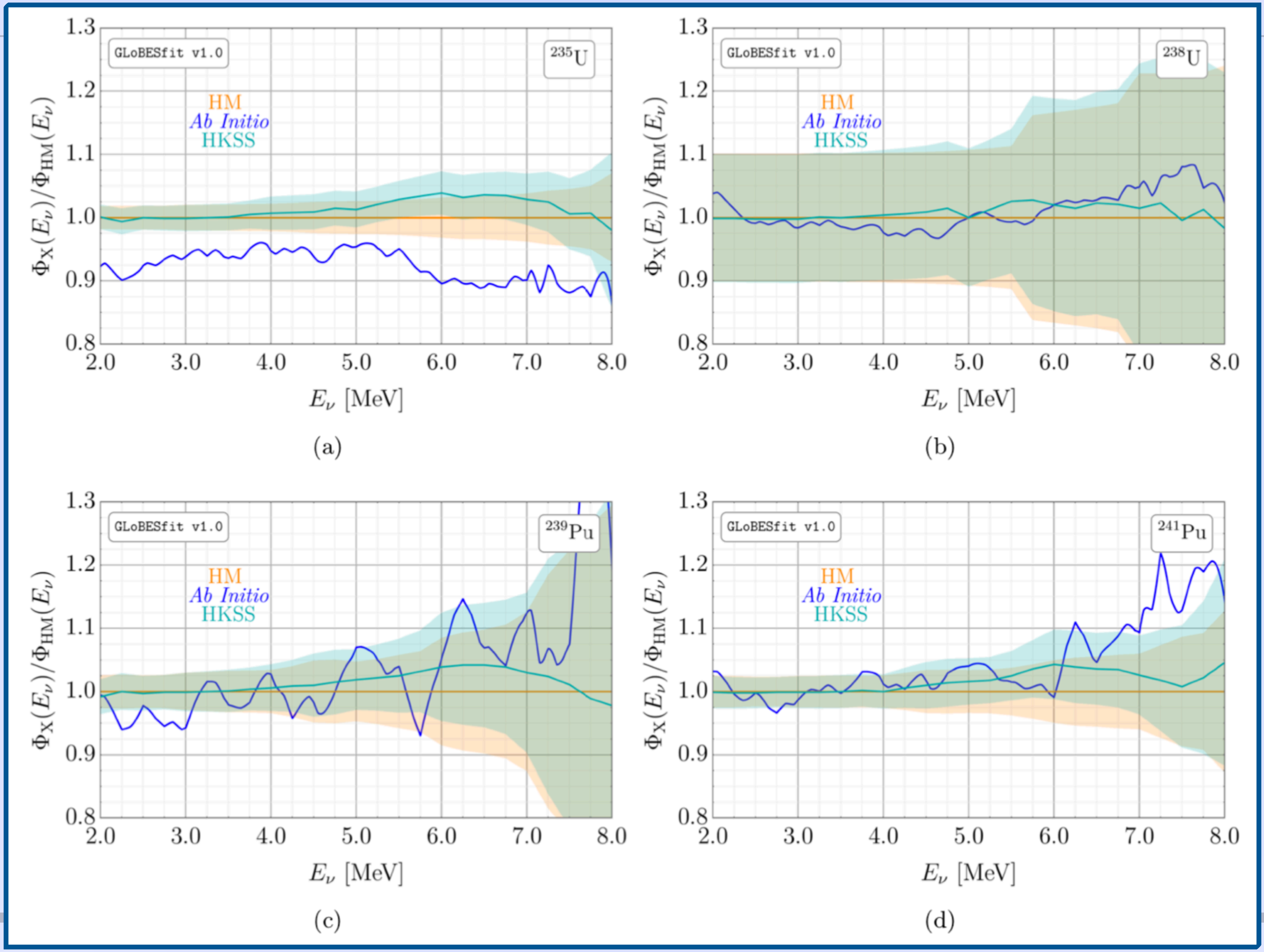
In 2019, two new reactor antineutrino flux predictions have appeared, each using different techniques!

Estienne, et al.: *Ab initio* calculation (but no uncertainty estimates)

Hayen, et al.: Conversion method with improved estimates of *forbidden* contributions – with uncertainties!

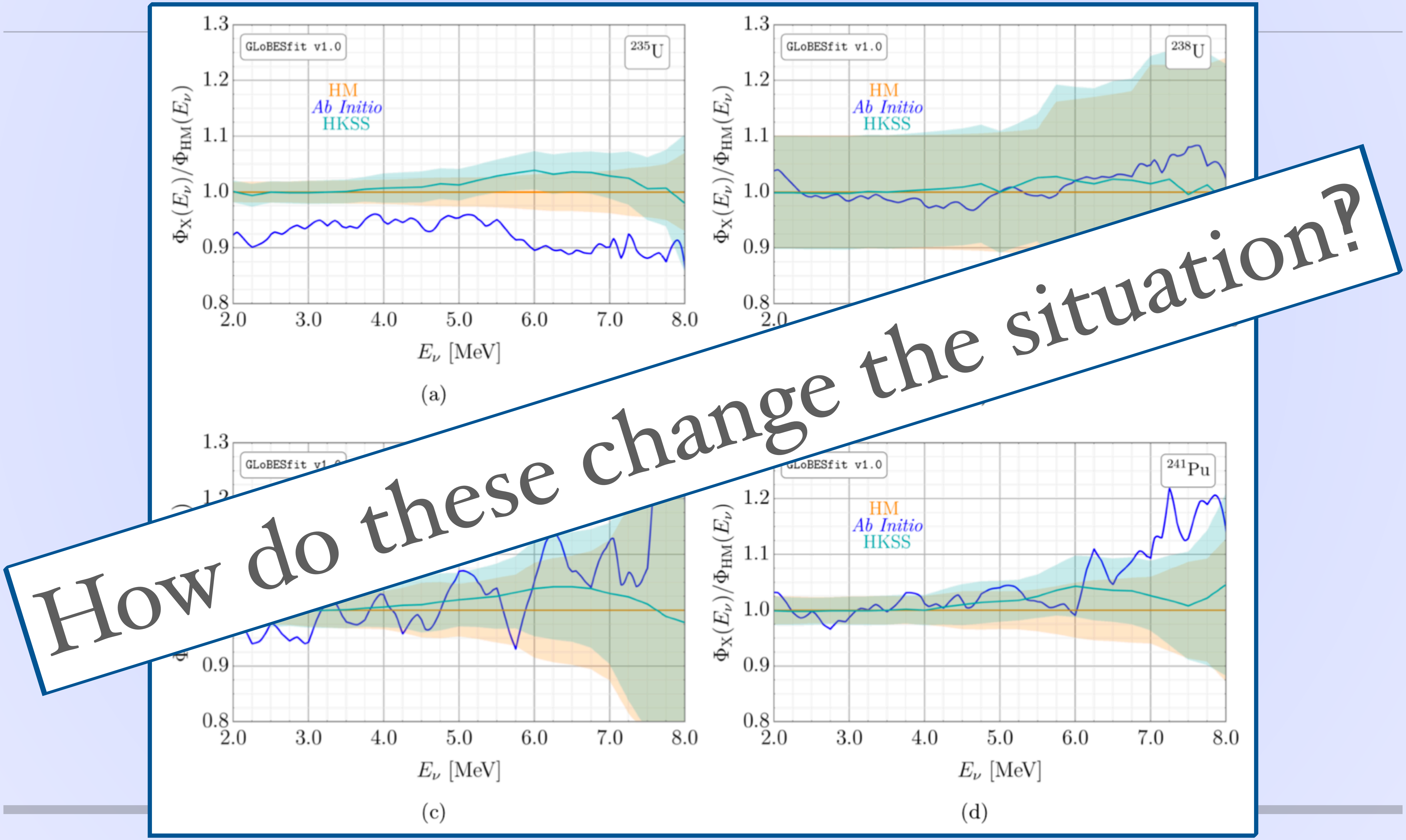
M. Estienne, et al., PRL 123 (2019) 022502;
L. Hayen, et al., PRC 99 (2019) 031301, PRC 100 (2019) 054323

New Flux Predictions



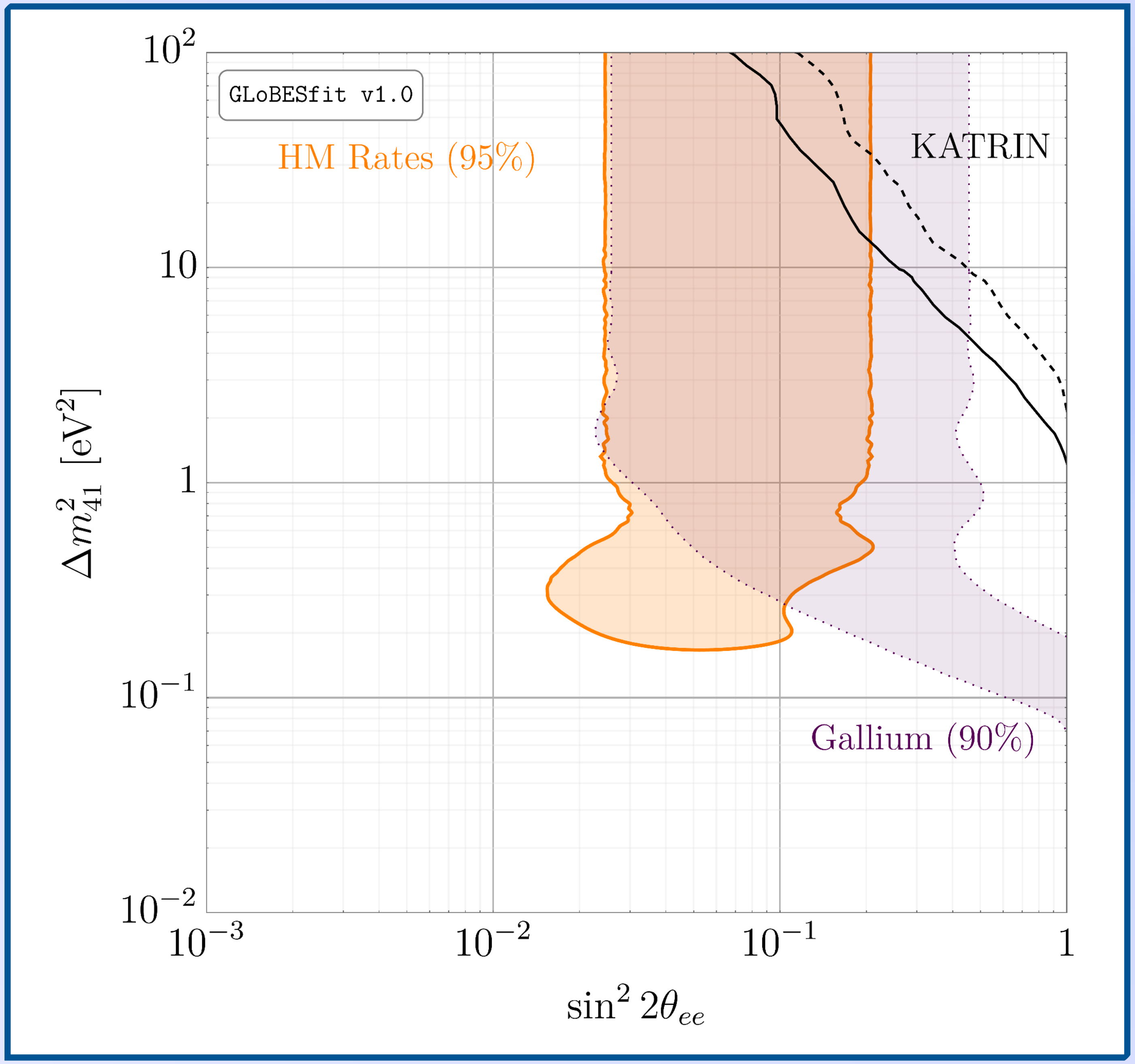
JMB & P. Huber, arXiv:2005.01756

New Flux Predictions



JMB & P. Huber, arXiv:2005.01756

All Rate Analyses



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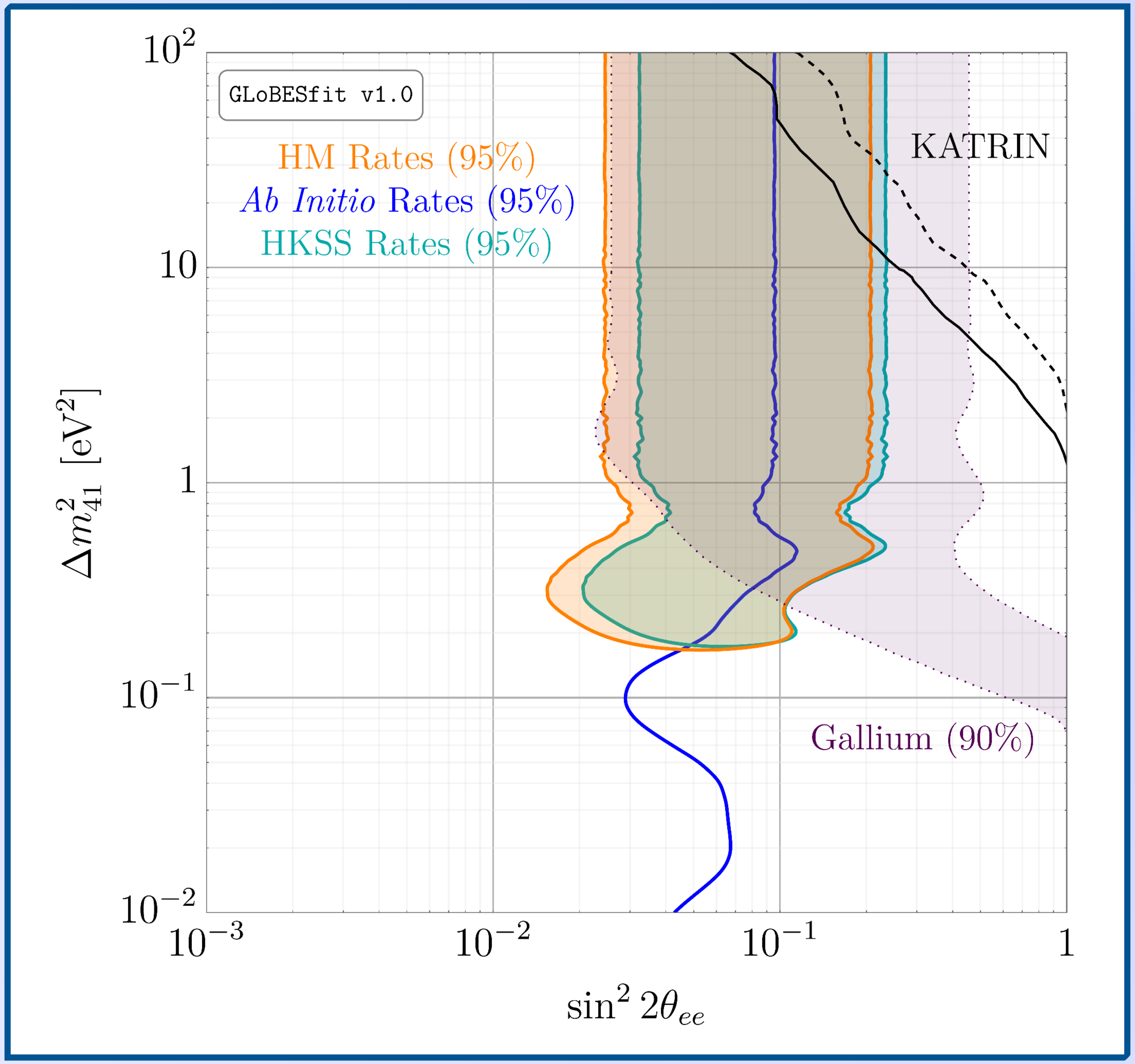
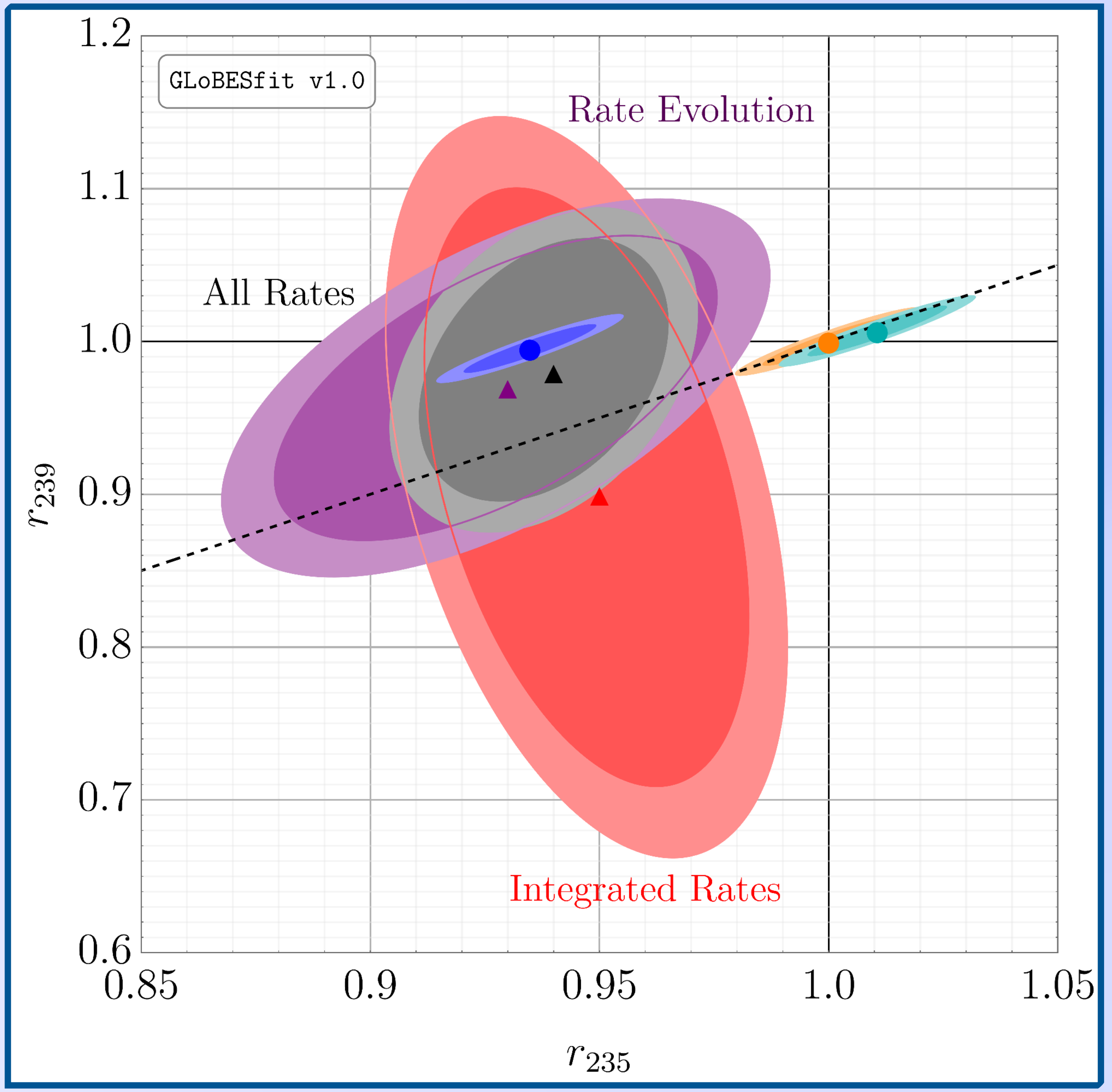


- These two new results *diverge* in their preference for a sterile neutrino!
  - HM Rates: 2.5σ
  - *Ab initio* Rates: 0.6σ
  - HKSS Rates: 2.6σ

Which one of these (if any) is the correct choice?

J. Kostensalo, et al., PLB 795 (2019) 542; C. Giunti, et al., JHEP05 (2020) 061;

Another View on Rates



- Alternatively, simply *rescale* the HM predictions for ^{235}U and ^{239}Pu!
- The data *slightly prefer* this over introducing a sterile neutrino
  - Rescaling: p = 0.88
  - Sterile: p = 0.78

JMB & P. Huber, arXiv:2005.01756

Analyzing Spectra

The experimental inputs we use are:

1. Bugey-3: Ratio of spectra at 15 m and 40 m; no 95 m (*25*)
2. DANSS: Ratio of spectra at 10.7 m and 12.7 m; no 11.7 m (*24*)
3. Daya Bay: Ratios of spectra – EH2/EH1 and EH3/EH1 (*52*)
4. Double Chooz: Ratio of spectra at near and far detectors (*26*)
5. NEOS: Ratio of NEOS data relative to antineutrino spectrum *measured at Daya Bay* (*60*)
6. RENO: Ratio of spectra at near and far detectors (*25*)

These ratios are (largely) independent of the particular flux model that we use in our analysis!

JMB & P. Huber, PRD 101 (2020) 015008; arXiv:2005.01756

Analyzing Spectra

- We compute a χ^2 function of the form

$$\boxed{\chi^2 = \sum_A (\vec{S}^A_{\text{exp}} - \vec{S}^A_{\text{pred}})^T \cdot (V_A)^{-1} \cdot (\vec{S}^A_{\text{exp}} - \vec{S}^A_{\text{pred}})}$$

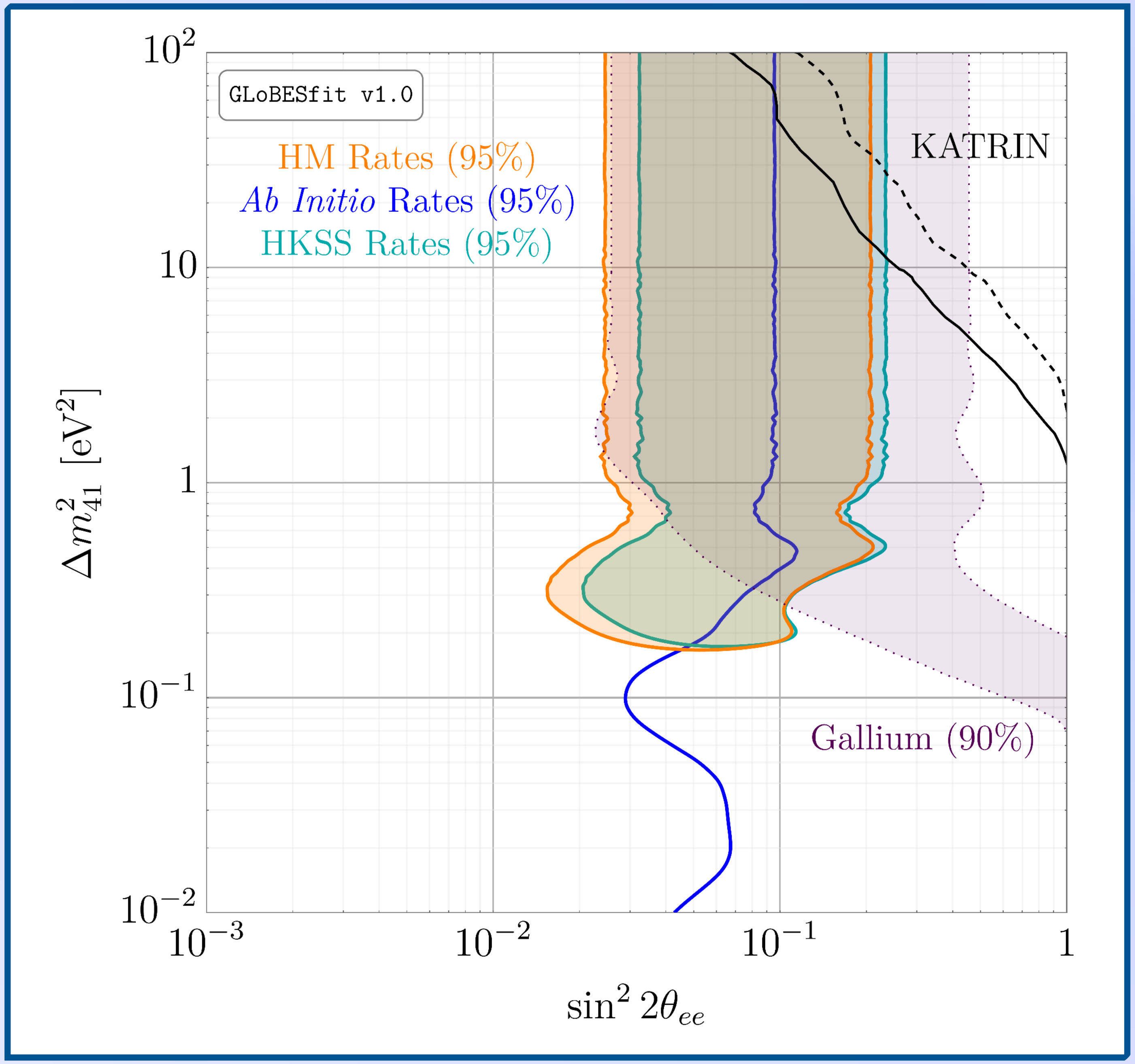
- For everyone *except NEOS*,

$$\boxed{\vec{S}^A_{\text{pred}} \sim \frac{N^A_{4\nu,\text{near}}}{N^A_{4\nu,\text{far}}}}$$

- For NEOS,

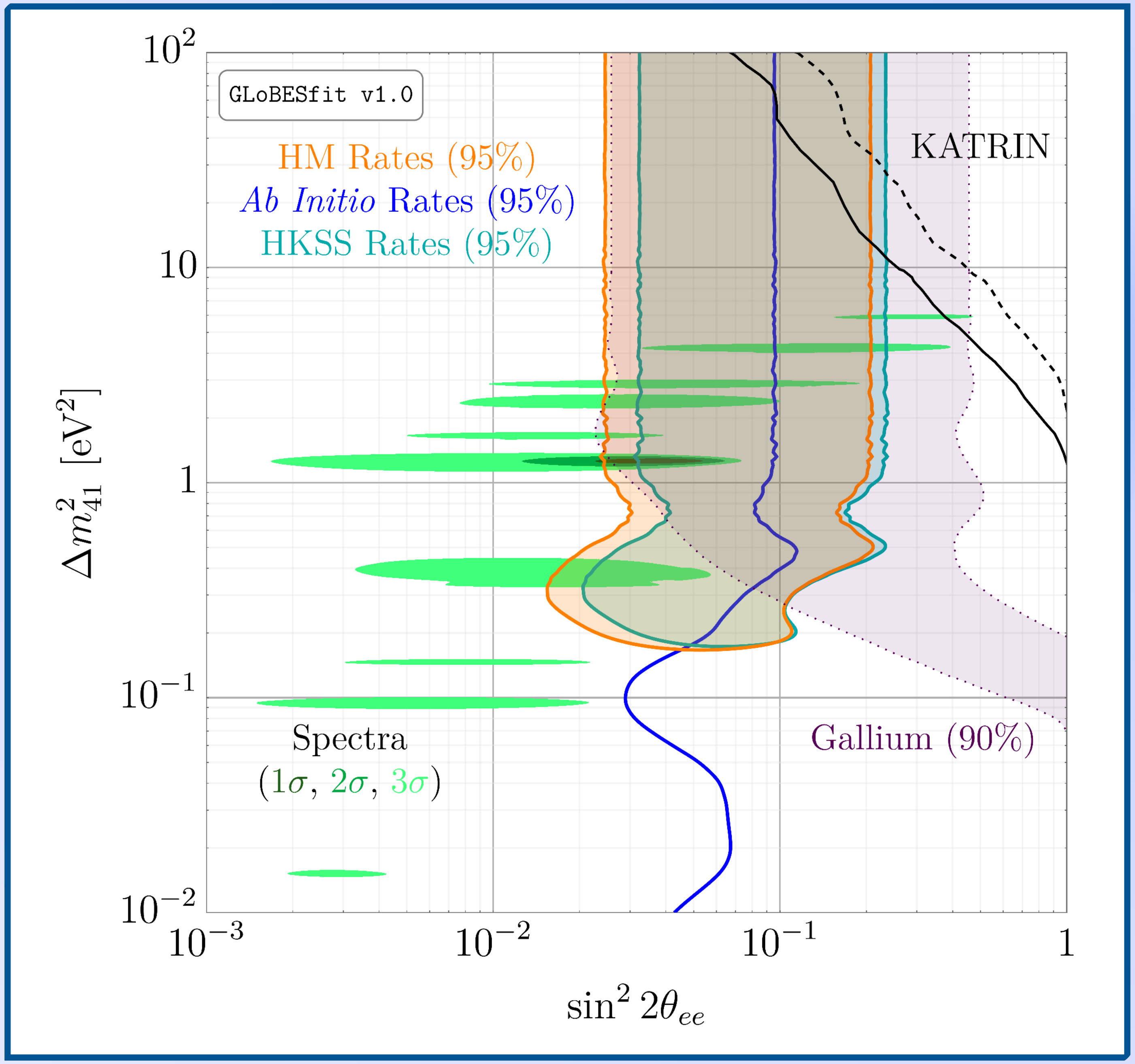
$$\boxed{\vec{S}^{\text{NEOS}}_{\text{pred}} \sim \frac{N^{\text{NEOS}}_{4\nu} / N^{\text{DB,EH1}}_{4\nu}}{N^{\text{NEOS}}_{3\nu} / N^{\text{DB,EH1}}_{3\nu}}}$$

Spectral Analysis



J. Kostensalo, et al., Phys. Lett. B795 (2019) 542; C. Giunti, et al., JHEP05 (2020) 061;

Spectral Analysis



- The evidence is modestly strong – 3.2σ*!
  - *DANSS+NEOS*: 3.3σ*!
- We don't combine rate and spectra – BUT:
  - Clearly consistent with *ab initio*
  - Mostly OK with HM and HKSS (but not *great*)

J. Kostensalo, et al., Phys. Lett. B795 (2019) 542; C. Giunti, et al., JHEP05 (2020) 061;

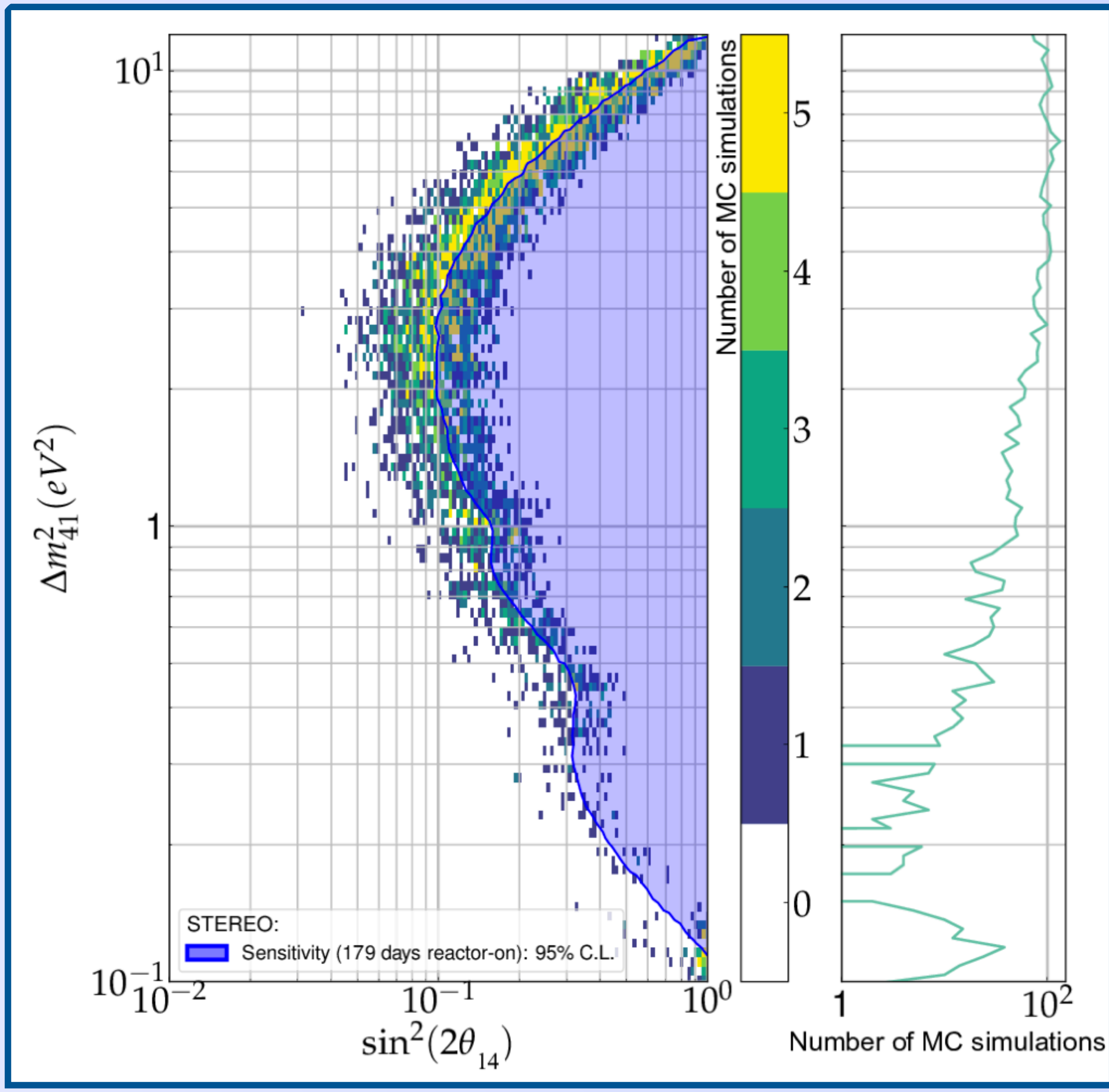
What Could Go Wrong?

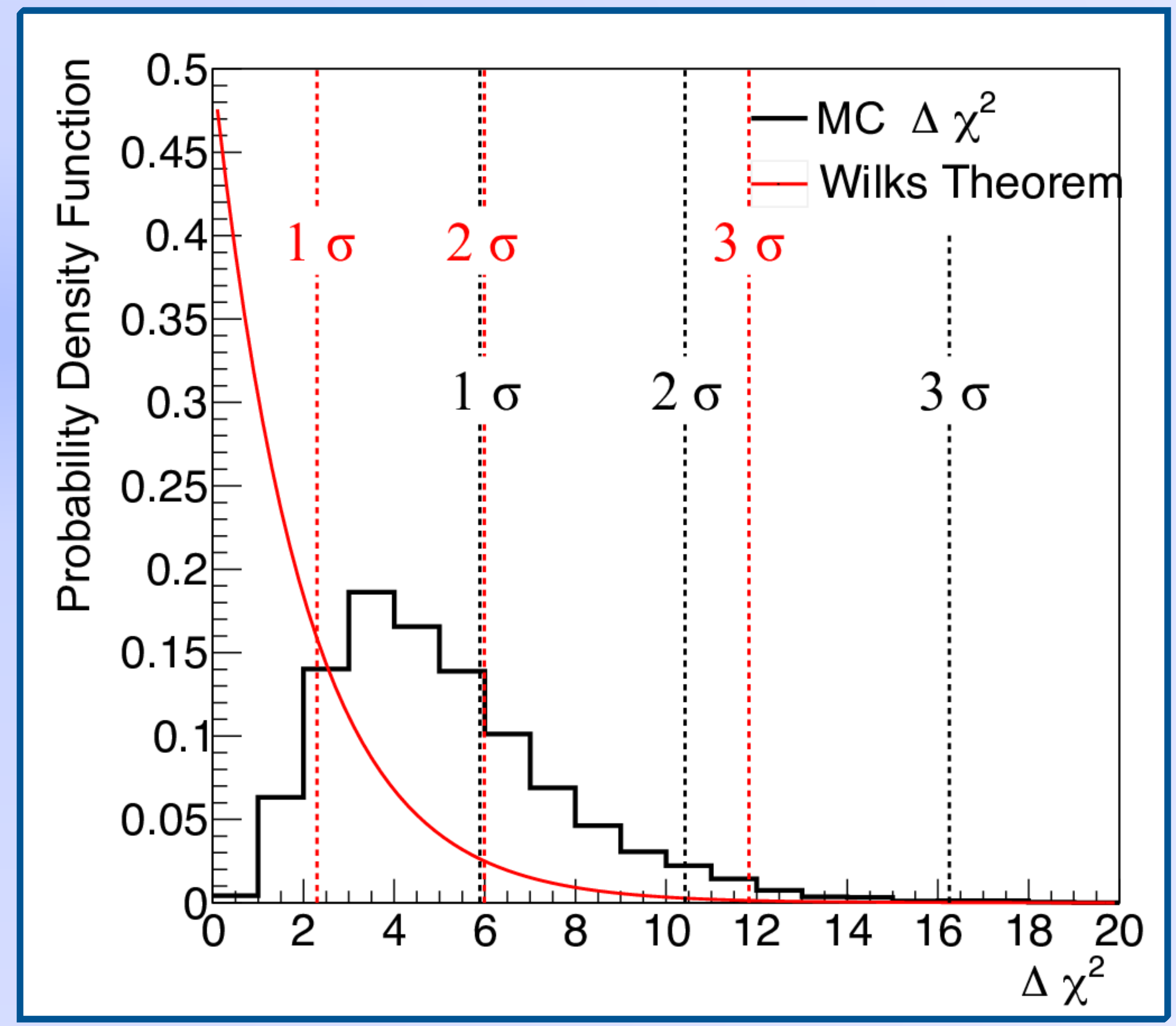
What are the ways in which this analysis is deficient?

1. Experimental analyses are *complicated*; exact replication is essentially impossible!
   (Lack of published data; experimental geometry; operating conditions; detector response models, etc.)
2. Statistical methods are *way* oversimplified!
   (Often not χ^2-distributed –*Wilks' theorem* may be invalid; e.g., $\Delta\chi^2$=6.18 may *actually* correspond to <2σ!)

(See A. Diaz, et al., arXiv:1906.00045; C. Giunti, PRD 101 (2020) 095025; PROSPECT & STEREO Collaborations, arXiv:2006.13147 for more discussion of these points)

Statistics In Action!

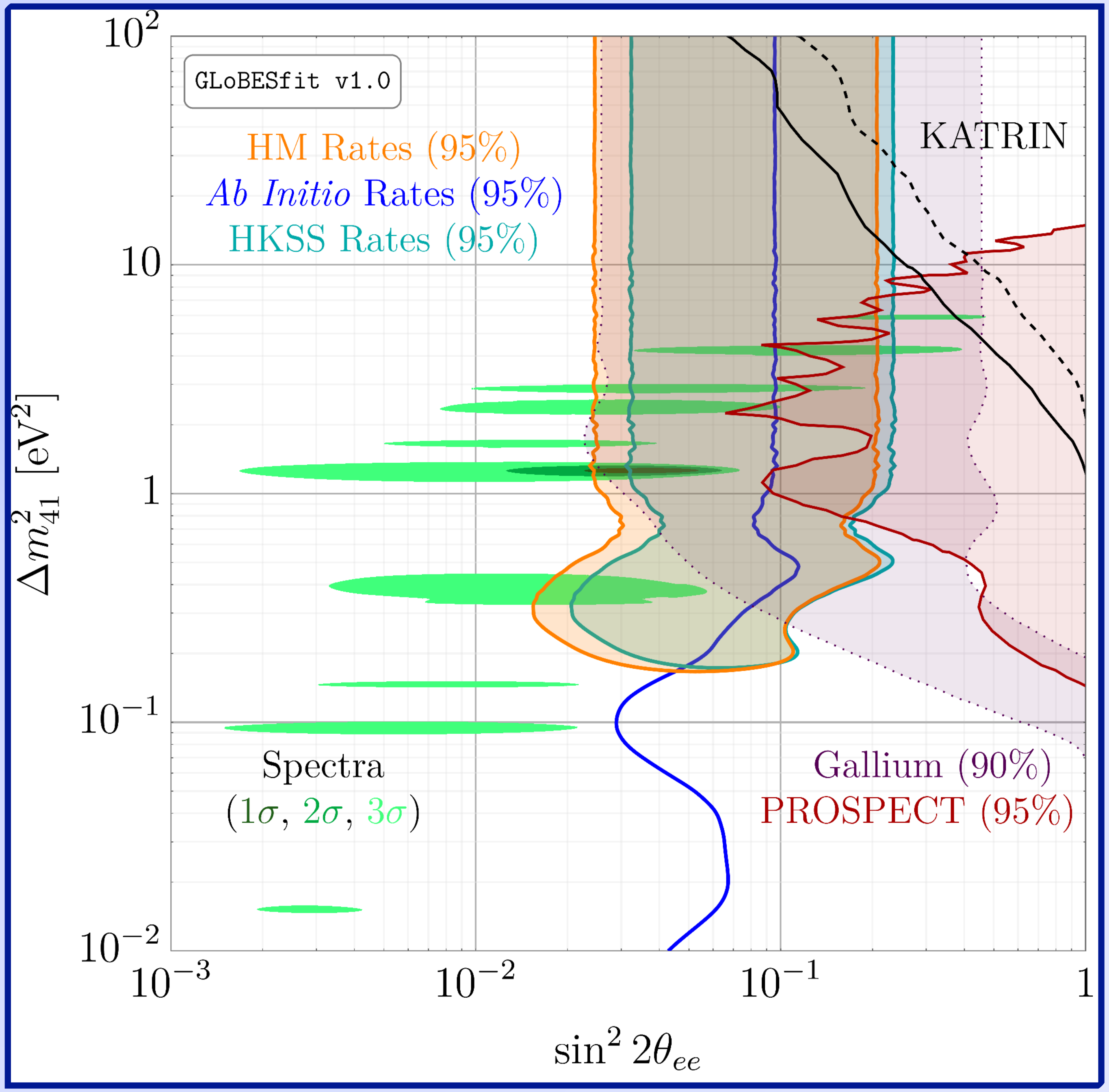




Part 3: So Now What?

PROSPECT

Current constraints from PROSPECT do not appear to be as competitive in the hunt for a sterile neutrino – perhaps opportunities for improvement?

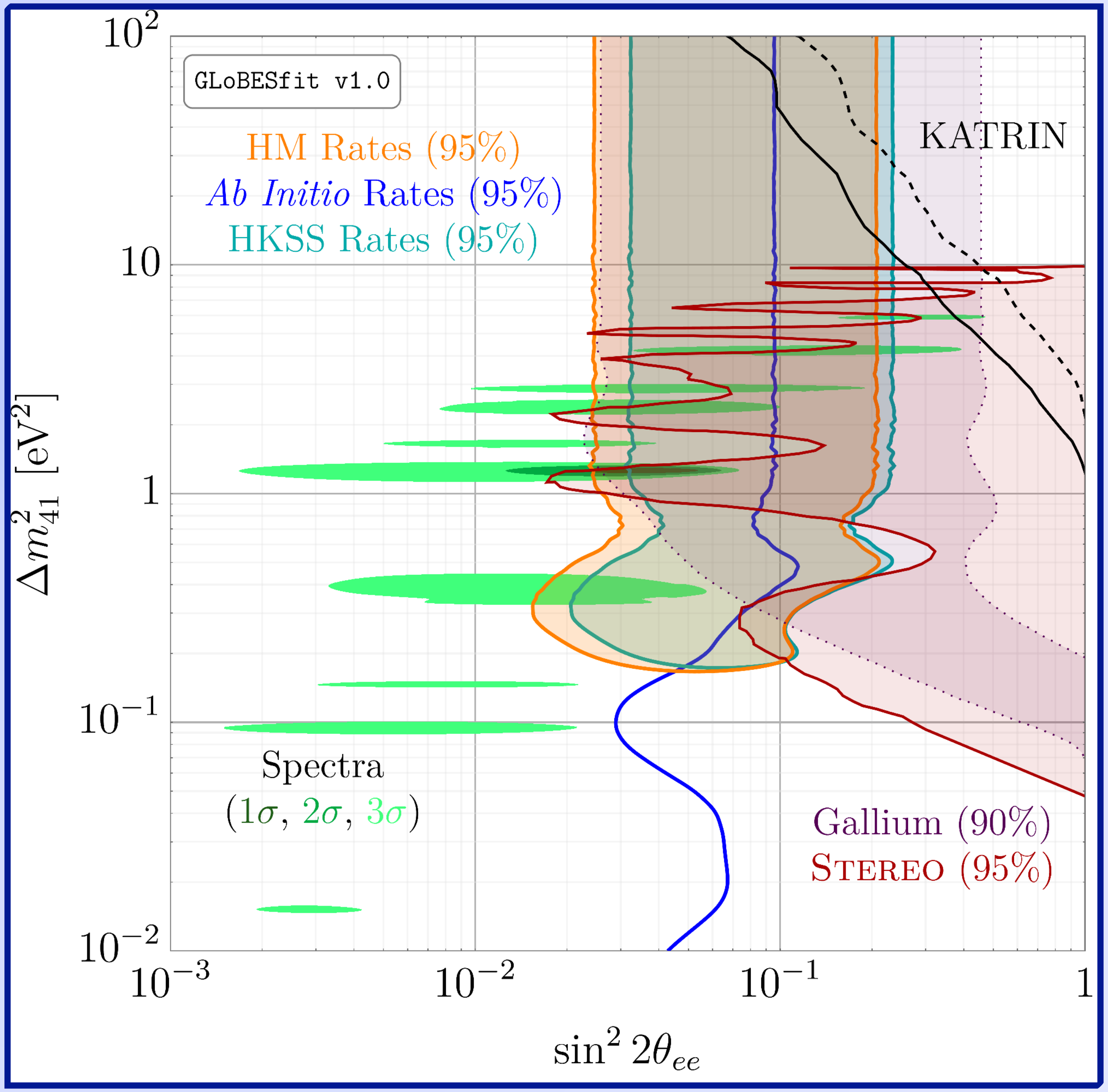


J. Kostensalo, et al., PLB 795 (2019) 542; C. Giunti, et al., JHEP05 (2020) 061; PROSPECT Collaboration, arXiv:2006.11210

STEREO

The latest result from STEREO (179 days) is already challenging the results of our spectral analysis!

This (and PROSPECT) will be included in future updates to ***`GLoBESfit`***



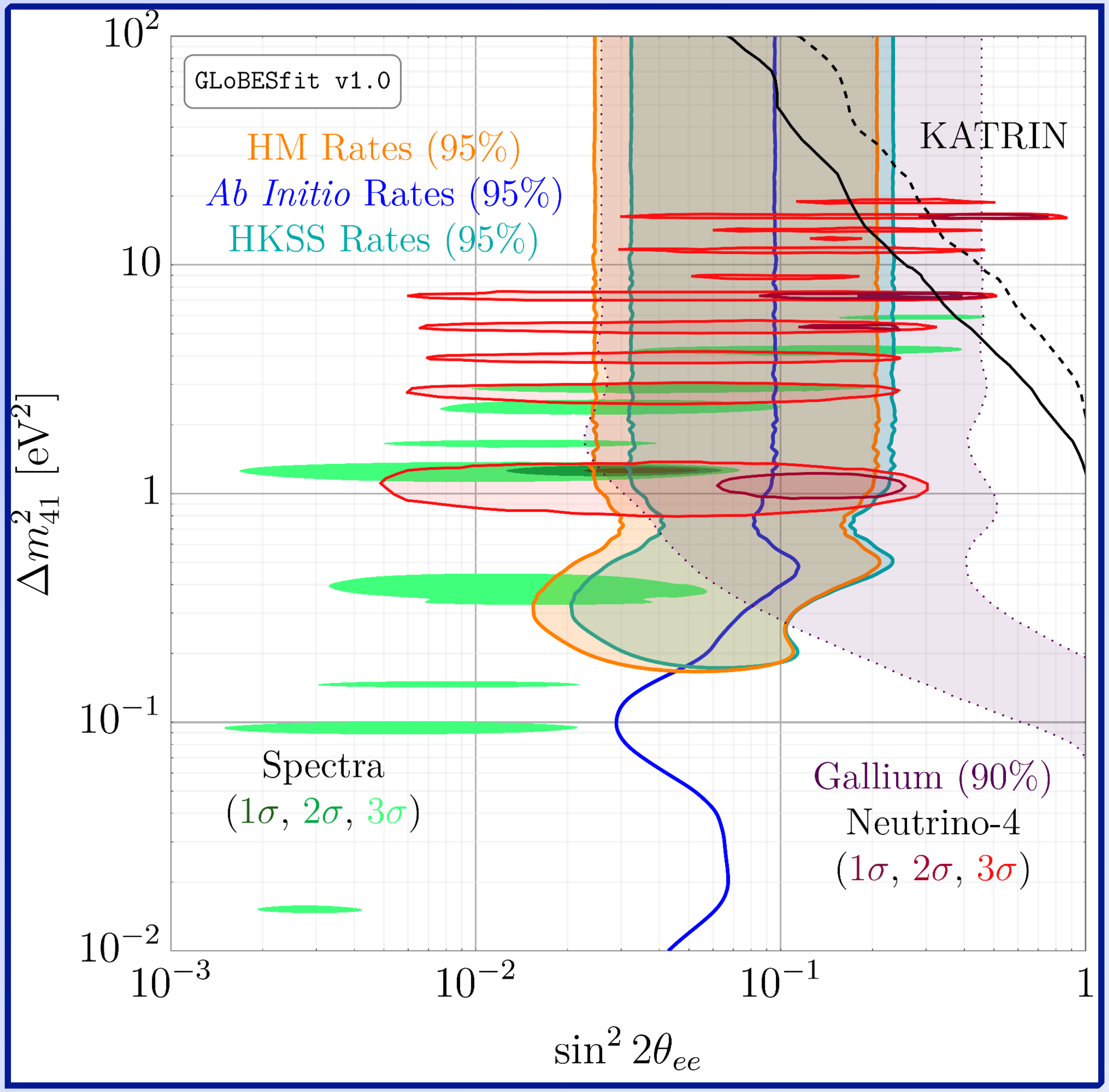
J. Kostensalo, et al., PLB 795 (2019) 542; C. Giunti, et al., JHEP05 (2020) 061; STEREO Collaboration, arXiv:1912.06582; S. Schoppmann @ Neutrino 2020

Neutrino-4

Neutrino-4 has been… *controversial*

See *arXiv:2006.13147* (PROSPECT & STEREO Collaborations) for discussion on the deficiencies of Neutrino-4's analysis

See *arXiv:2006.13639* for Neutrino-4's response



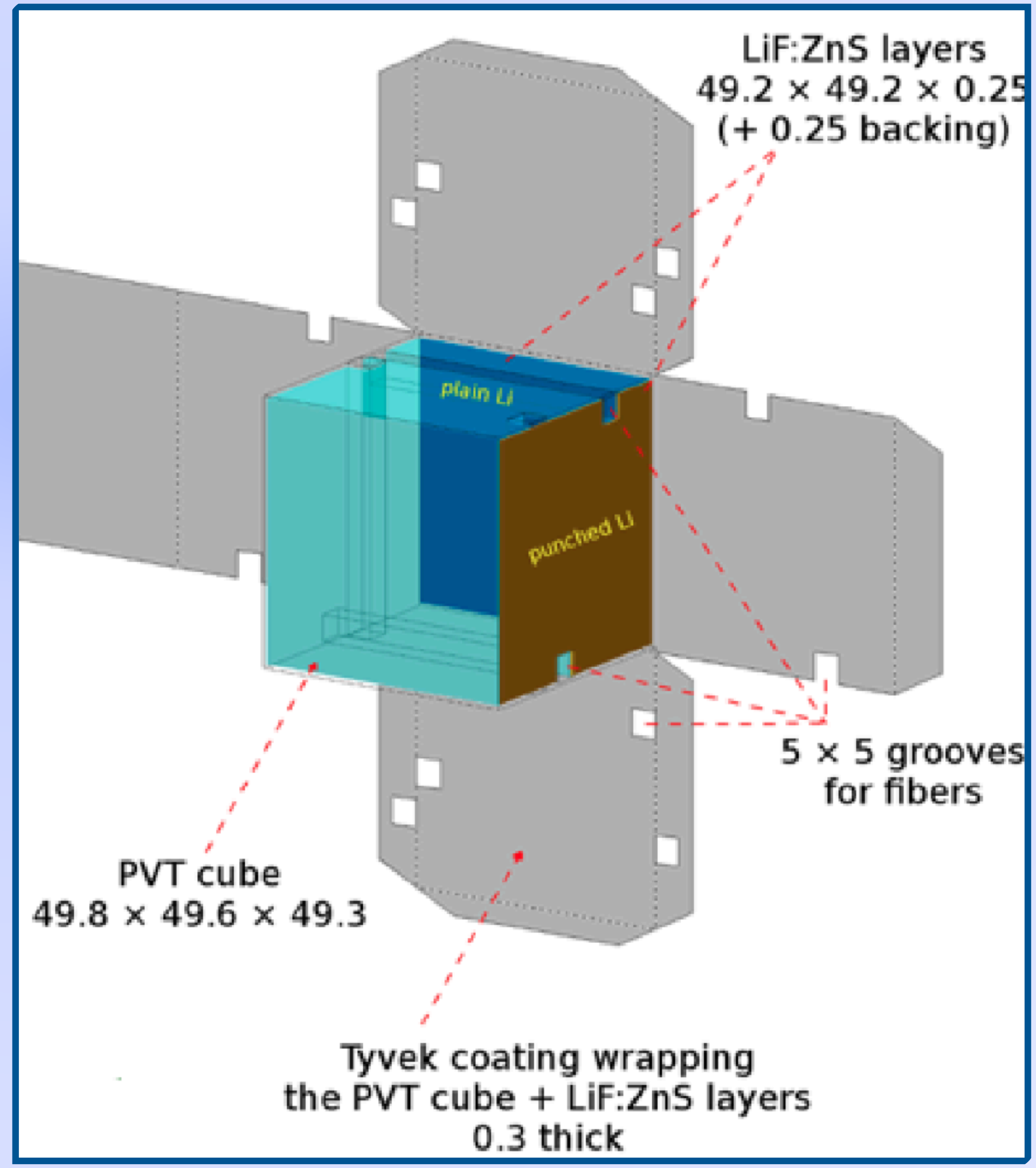
J. Kostensalo, et al., PLB 795 (2019) 542; C. Giunti, et al., JHEP 05 (2020) 061; A. Serebrov @ AAP 2019

SoLid

SoLid has been taking data between 6-9 m from BR2 reactor at SCK•CEN in Belgium since Spring 2018

A *highly segmented* detector – 12,800 PVT "cubes" wrapped in ^{6}LiF:ZnS(Ag) and tyvek

First physics results…soon?



J. Kostensalo, et al., PLB 795 (2019) 542; C. Giunti, et al., JHEP 05 (2020) 061;
SoLid Collaboration, J. Phys. Conf. Ser. 1342 (2020) 012034; arXiv:arXiv:2002.05914

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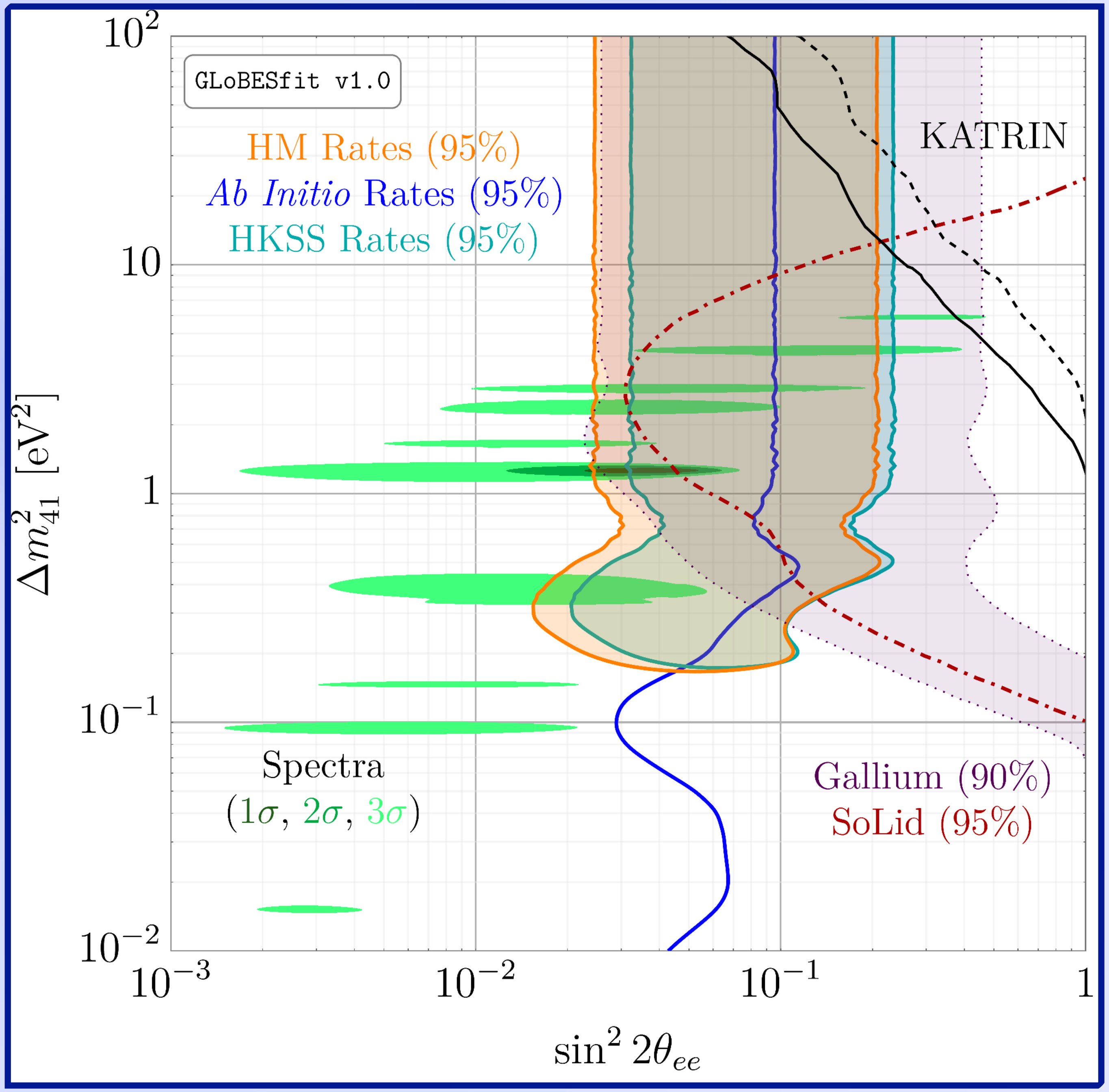


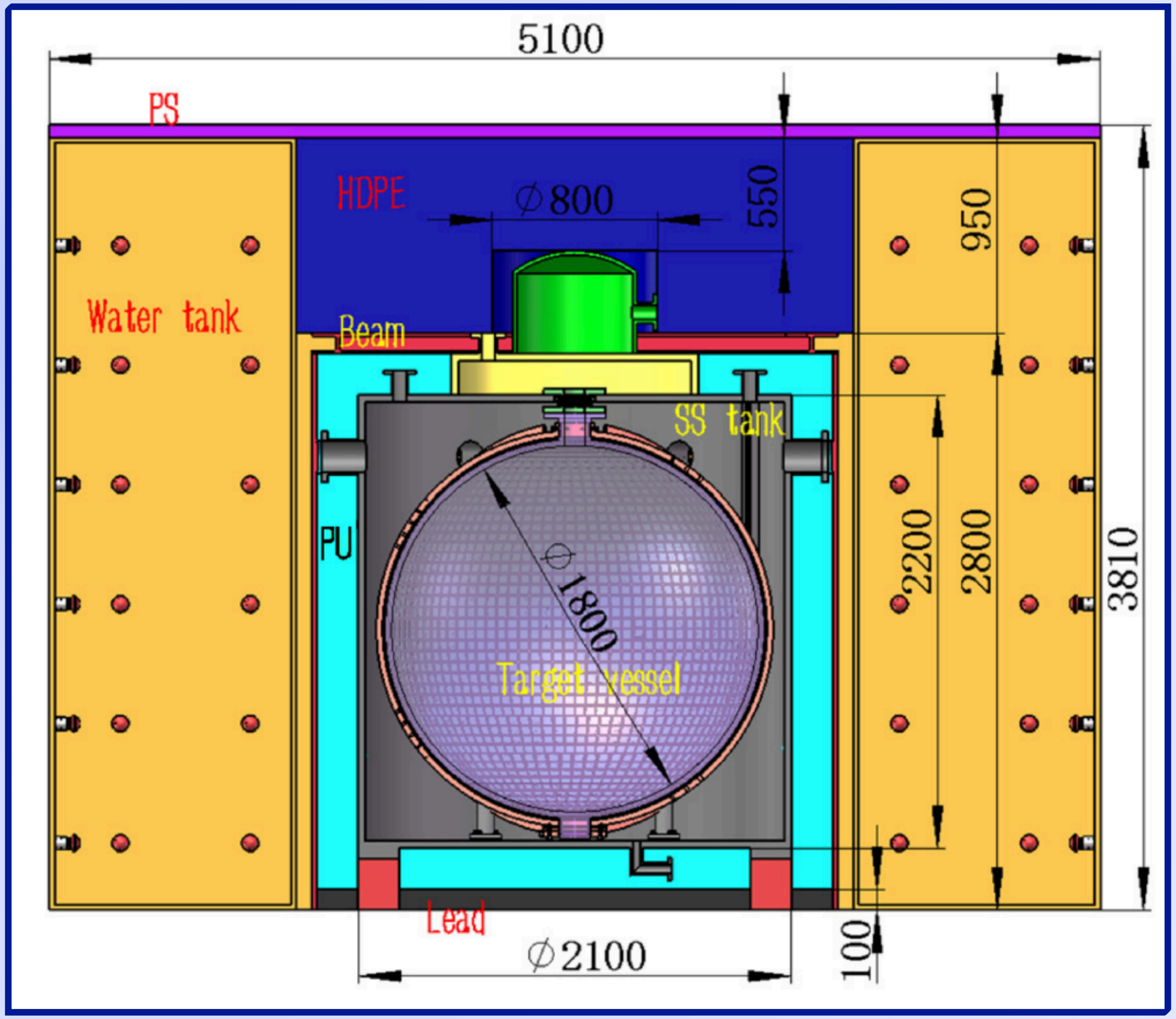
J. Kostensalo, et al., PLB 795 (2019) 542; C. Giunti, et al., JHEP 05 (2020) 061; SoLid Collaboration, J. Phys. Conf. Ser. 1342 (2020) 012034; arXiv:arXiv:2002.05914

Longer Term – JUNO-TAO

As part of the JUNO project, a smaller near detector will be constructed at Taishan NPP

Part of its physics mission will be a sterile neutrino search

Will feature *subpercent* energy resolution



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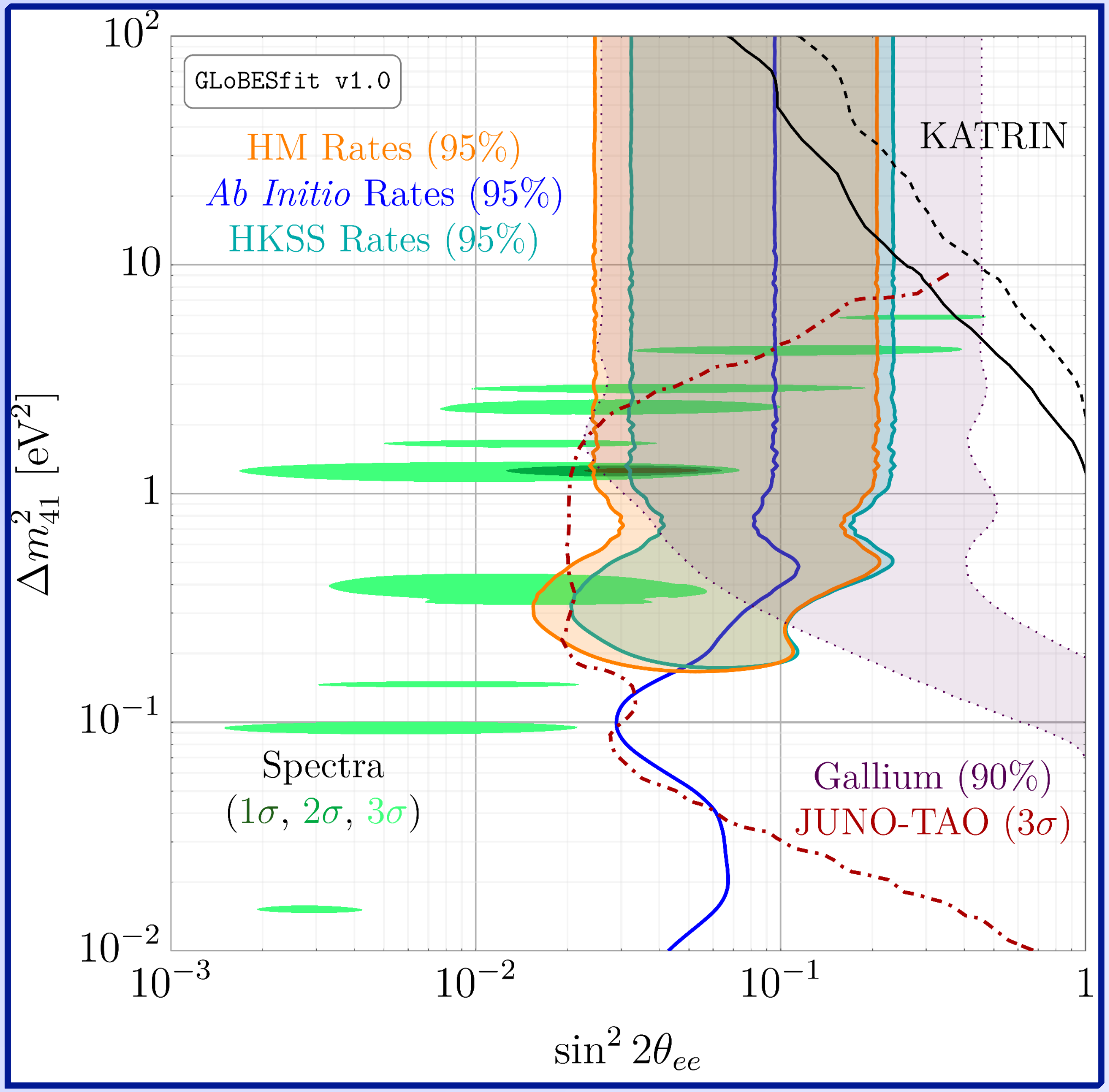

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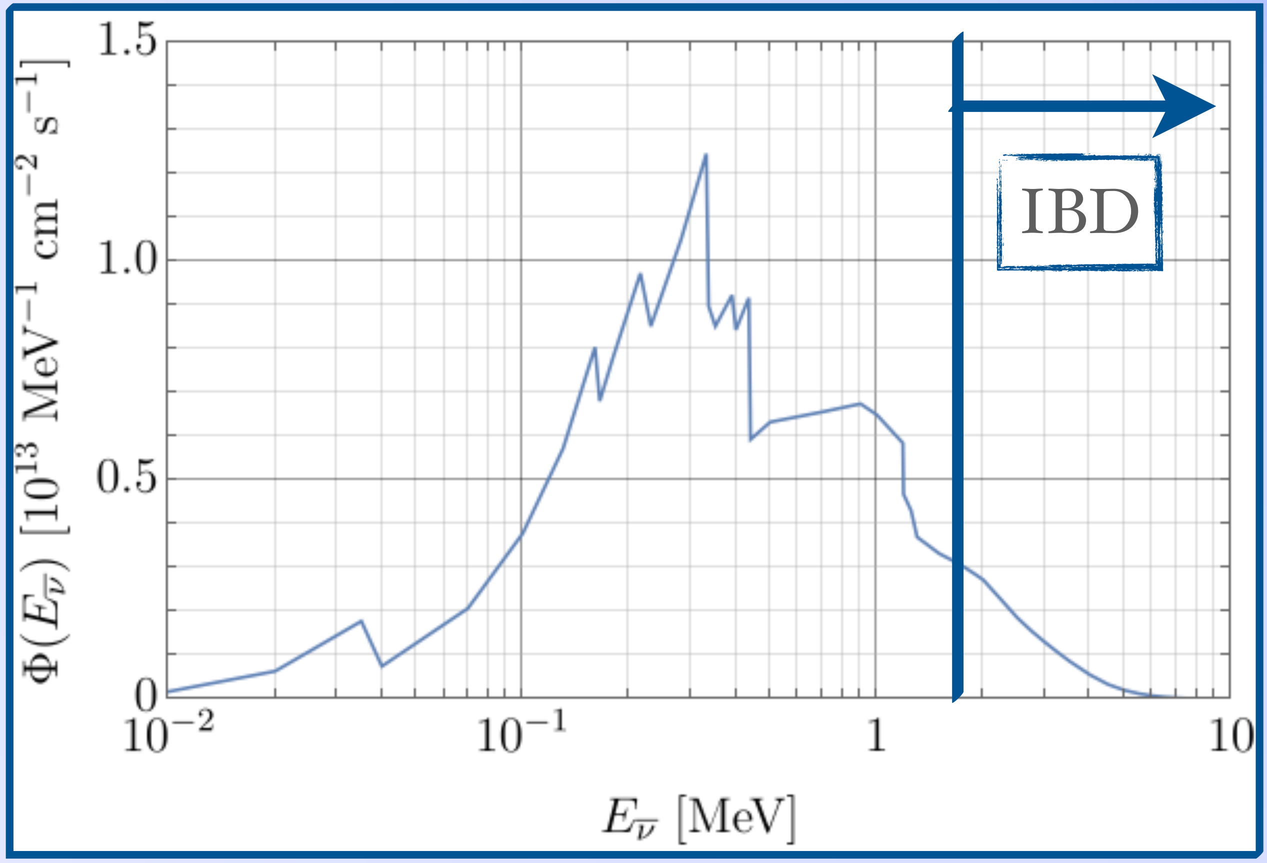
Longer Term – Beyond IBD

The detection of CEνNS opens up a new avenue by which to observe reactor antineutrinos – but comes with its share of challenges



Experiment	Detector	Energy threshold	Status
CONUS	Ge ionization	O(1keV$_{nr}$)	Running
TEXONO	Ge ionization	O(1keV$_{nr}$)	Running
Nu-GEN	Ge ionization	O(1keV$_{nr}$)	commissioning
RED-100	Liquid Xe TPC	O(1keV$_{nr}$)	Construction
CONNIE	CCD (Si)	~300eV$_{nr}$	running
MINER	Cryogenic (mK)	O(100eV$_{nr}$)	commissioning
RICOCHET	Cryogenic (mK)	55eV$_{nr}$	construction
NUCLEUS	Cryogenic (mK)	20eV$_{nr}$	construction

V. I. Kopeikin, Phys. Atom. Nucl. 75 (2012) 143; R. Strauss @ Neutrino 2020; J. Kostensalo, et al., PLB 795 (2019) 542; C. Giunti, et al., JHEP05 (2020) 061; JMB, PRD 100 (2019) 023540; B.C. Cañas, et al., PLB 776 (2018) 451

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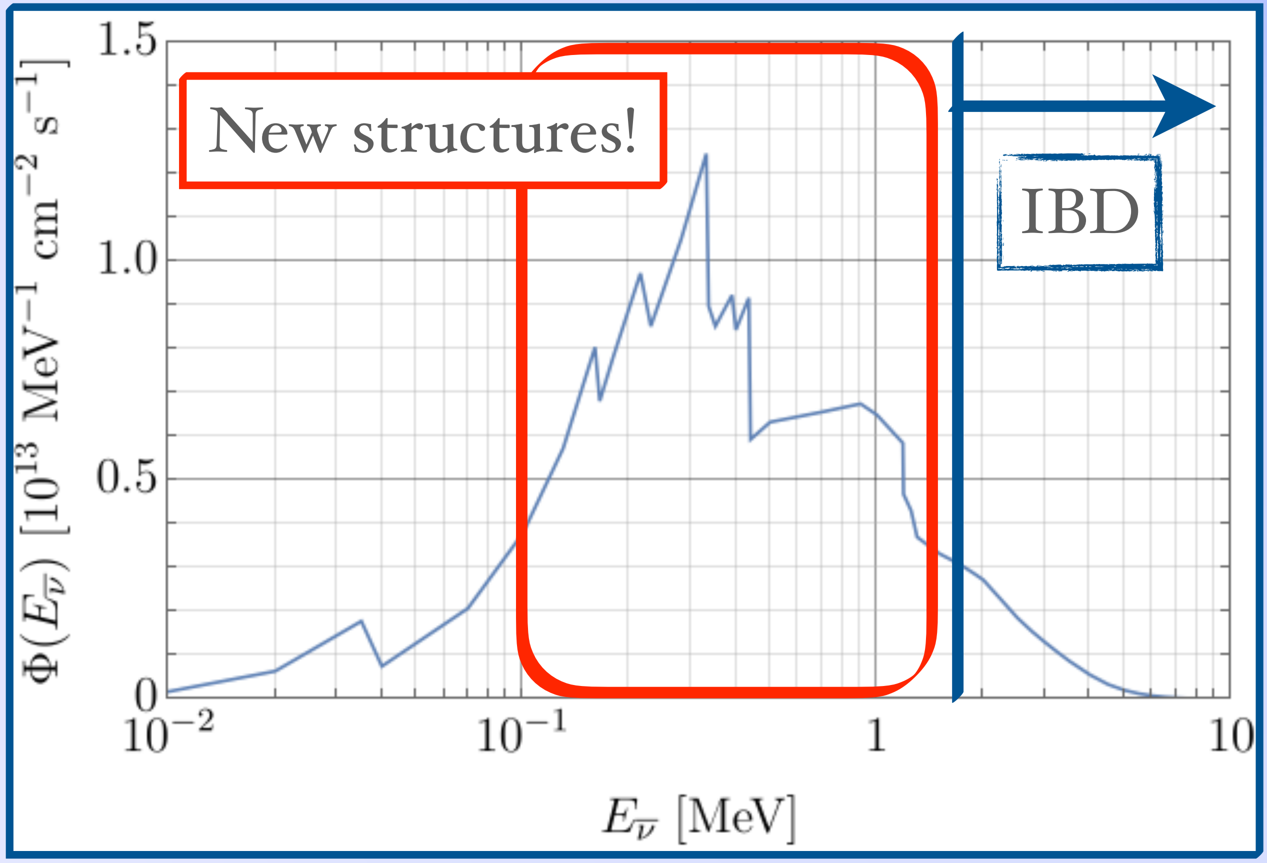

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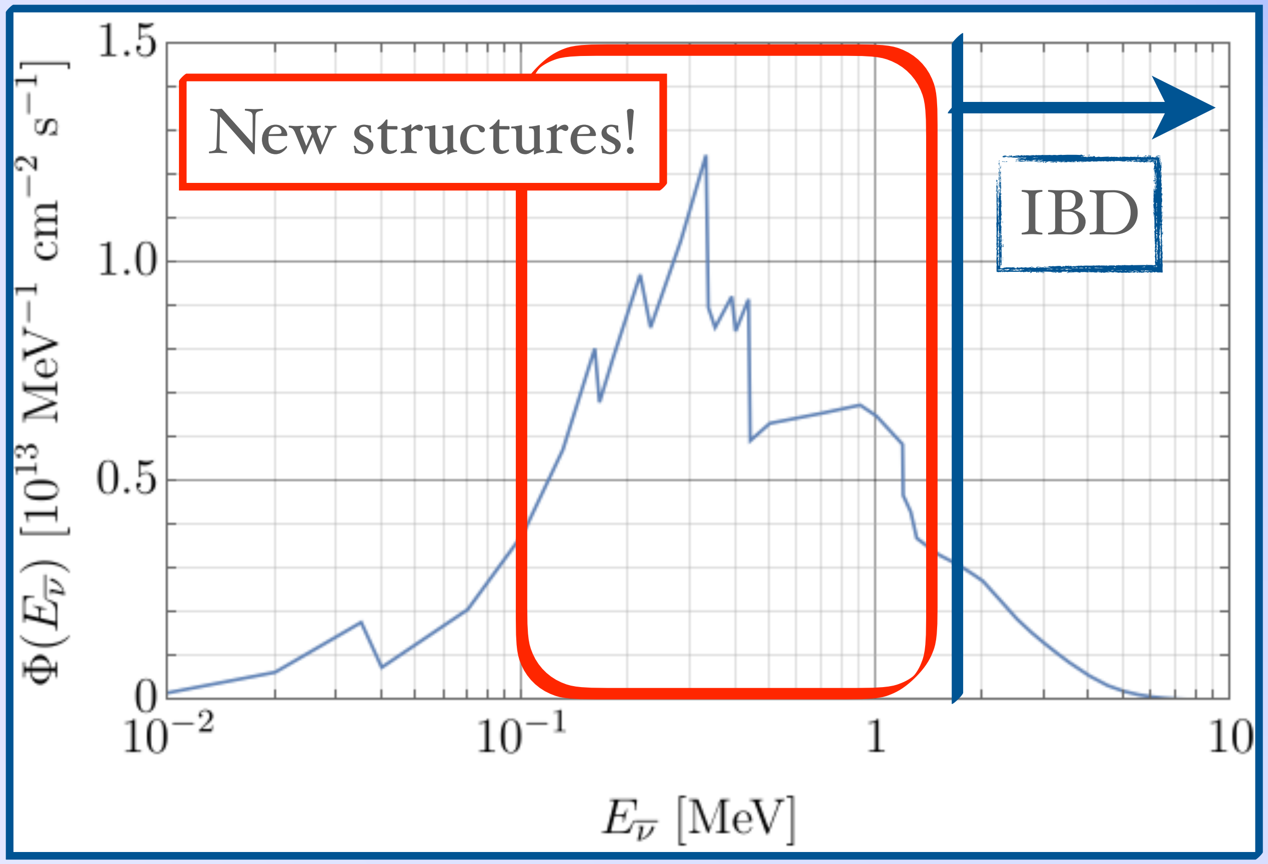

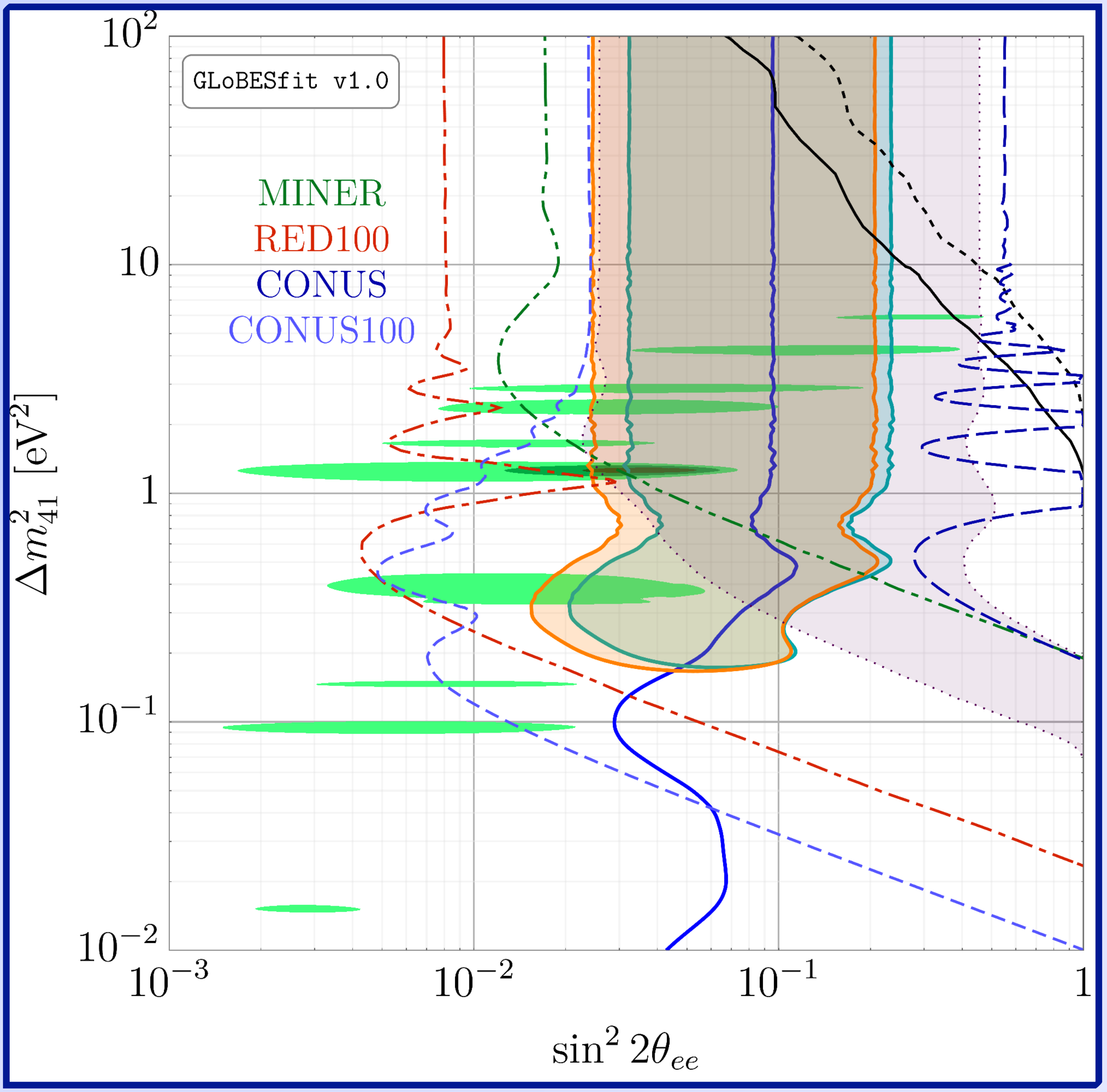

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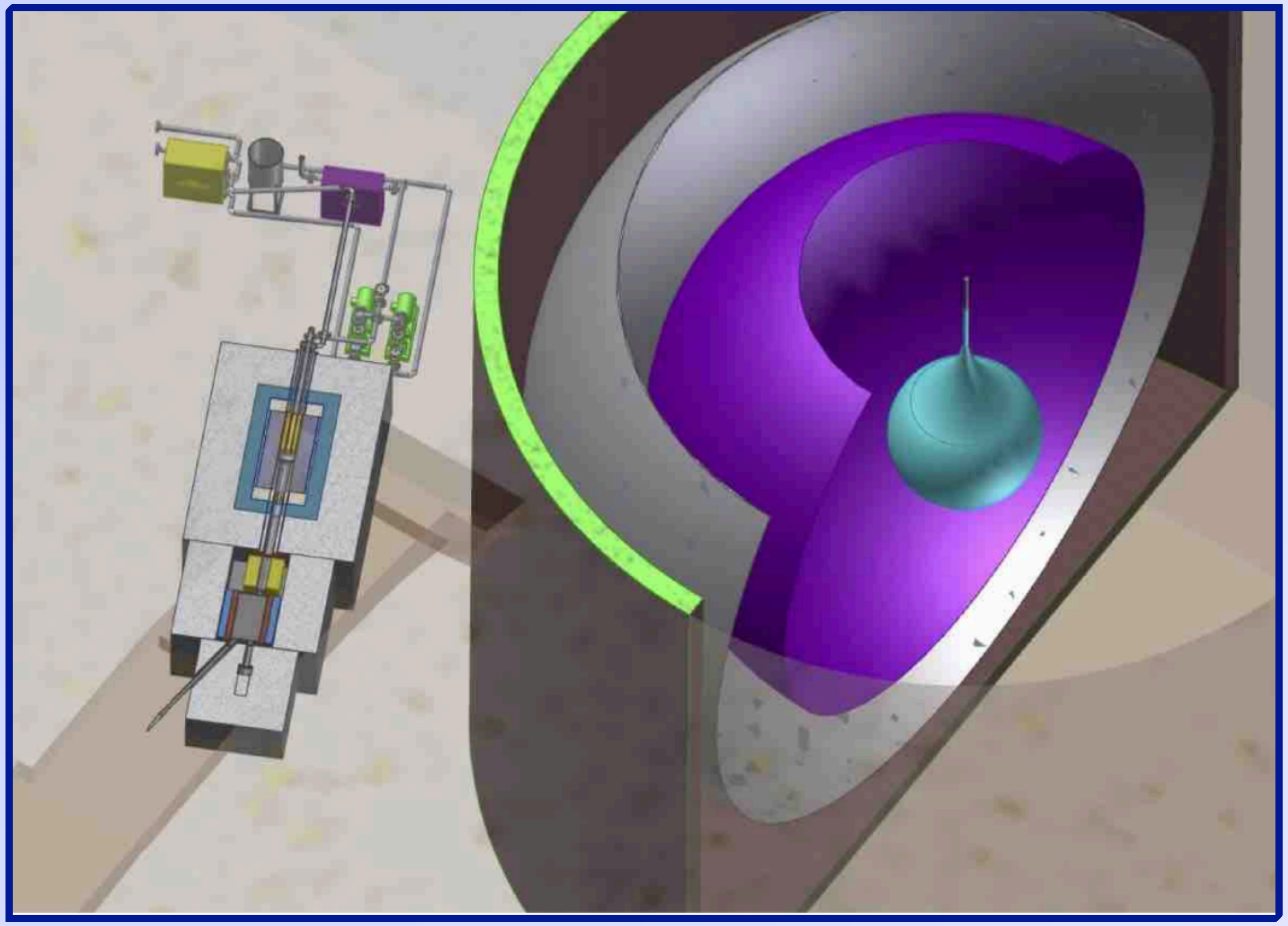
Even Longer Term – IsoDAR

Not a *reactor* experiment – proposal for beam-driven ^{8}Li β-decay source

Sensitivity here assumes five years of operation at *KamLAND*

Would expect an emphatic rejection (or acceptance) – *if it ever gets built*



J. Kostensalo, et al., PLB 795 (2019) 542; C. Giunti, et al., JHEP05 (2020) 061; IsoDAR Collaboration, arXiv:1710.09325

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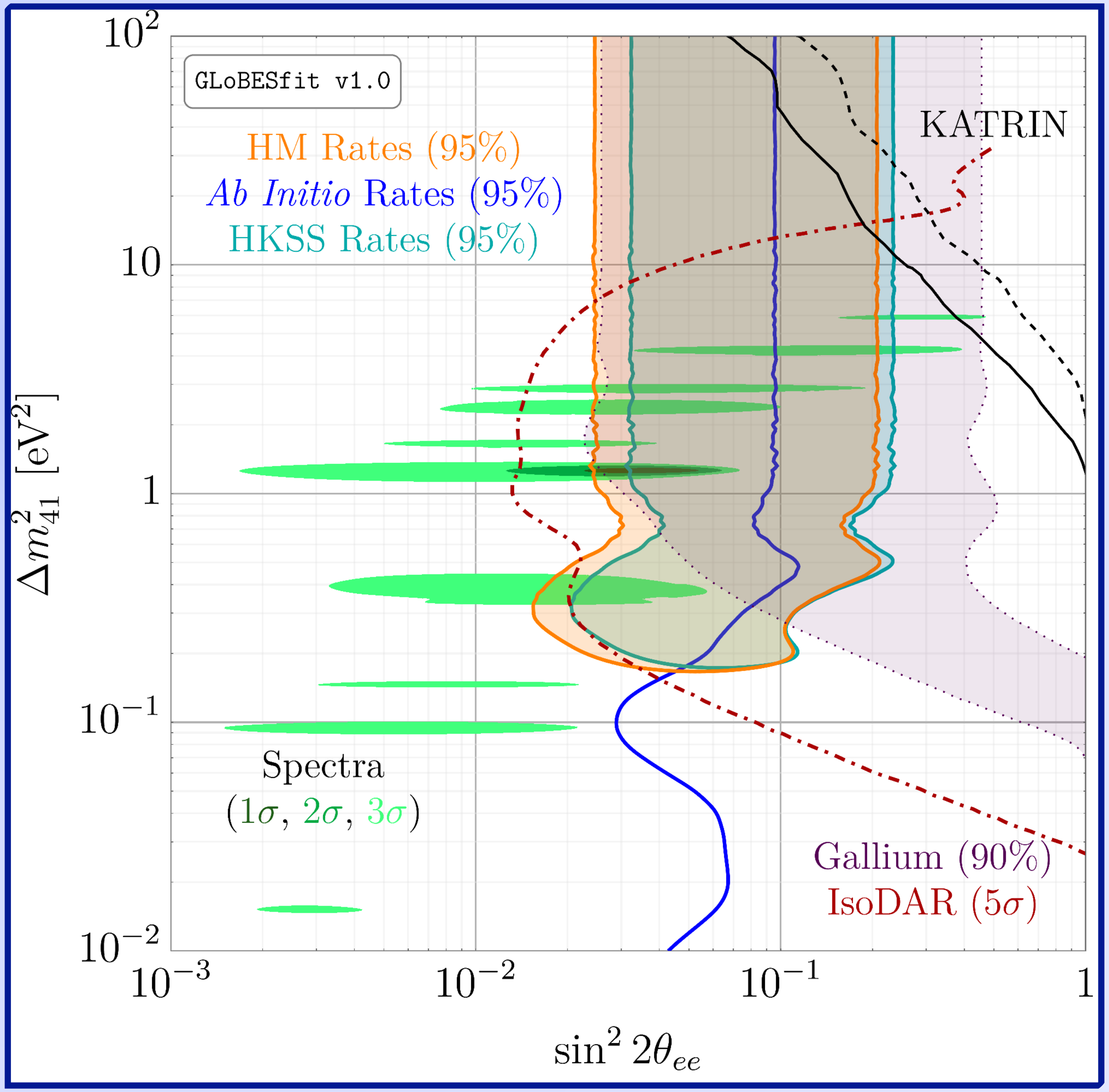

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Conclusions

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- **The Impact of Flux Predictions on Evidence for Sterile Neutrinos is *Really* Nontrivial**
  - How data are analyzed dictates the strength of the evidence inferred. This, in turn, dictates which experiments we conduct next!
- **The Sterile Neutrino Question Has *Far-Reaching* Consequences**
  - Cosmology already *strongly disfavors* an eV-scale sterile neutrino. If the reactor anomaly is borne out, then there *must* be some other ingredients to make the whole picture work!

Let’s see what happens over the next decade!

Thank you for your attention!

Back-Up

Conversion Method

Classification	ΔJ^π	Operator	Shape Factor $C(E_e)$	Fractional Weak Magnetism Correction $\delta_{\mathrm{WM}}(E_e)$
Allowed GT	1^+	$\Sigma \equiv \sigma\tau$	1	$\frac{2}{3}\left[\frac{\mu_v - 1/2}{M_N g_A}\right](E_e\beta^2 - E_\nu)$
Non-unique 1^{st} Forbidden GT	0^-	$[\Sigma, r]^{0-}$	$p_e^2 + E_\nu^2 + 2\beta^2 E_\nu E_e$	0
Non-unique 1^{st} Forbidden ρ_A	0^-	$[\Sigma, r]^{0-}$	λE_0^2	0
Non-unique 1^{st} Forbidden GT	1^-	$[\Sigma, r]^{1-}$	$p_e^2 + E_\nu^2 - \frac{4}{3}\beta^2 E_\nu E_e$	$\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu)+2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2+E_\nu^2-4\beta^2 E_\nu E_e/3)}\right]$
Unique 1^{st} Forbidden GT	2^-	$[\Sigma, r]^{2-}$	$p_e^2 + E_\nu^2$	$\frac{3}{5}\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu)+2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2+E_\nu^2)}\right]$
Allowed F	0^+	τ	1	0
Non-unique 1^{st} Forbidden F	1^-	$r\tau$	$p_e^2 + E_\nu^2 + \frac{2}{3}\beta^2 E_\nu E_e$	0
Non-unique 1^{st} Forbidden $\vec{J}_V$	1^-	$r\tau$	E_0^2	-

The important point: the shape factor deviates from unity (possibly quite dramatically) for forbidden decays – which constitute ~30% of decays in a reactor

Conversion Method

NB: Not the same C as in the expression for the spectrum (here, weak finite-size correction)

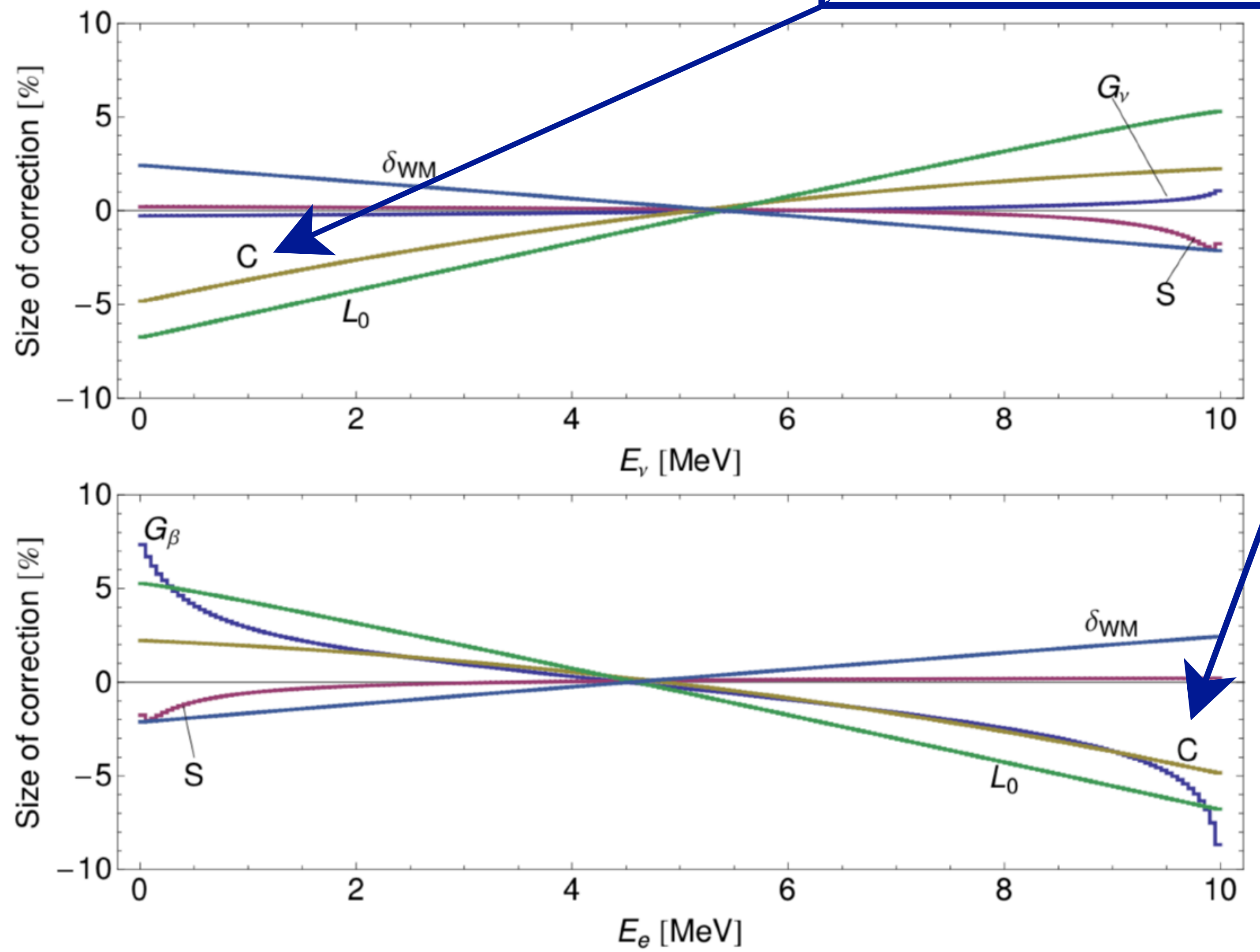
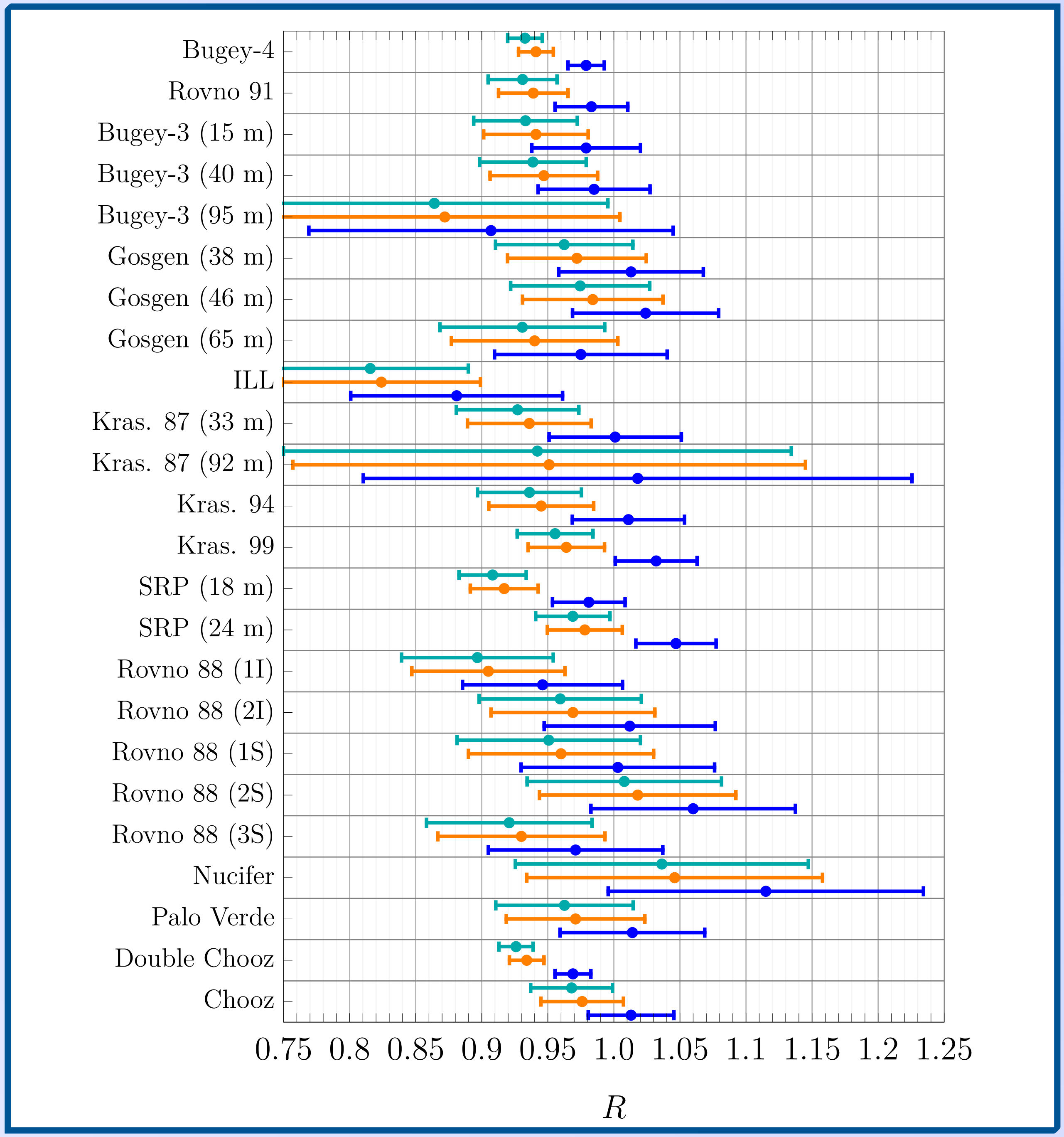
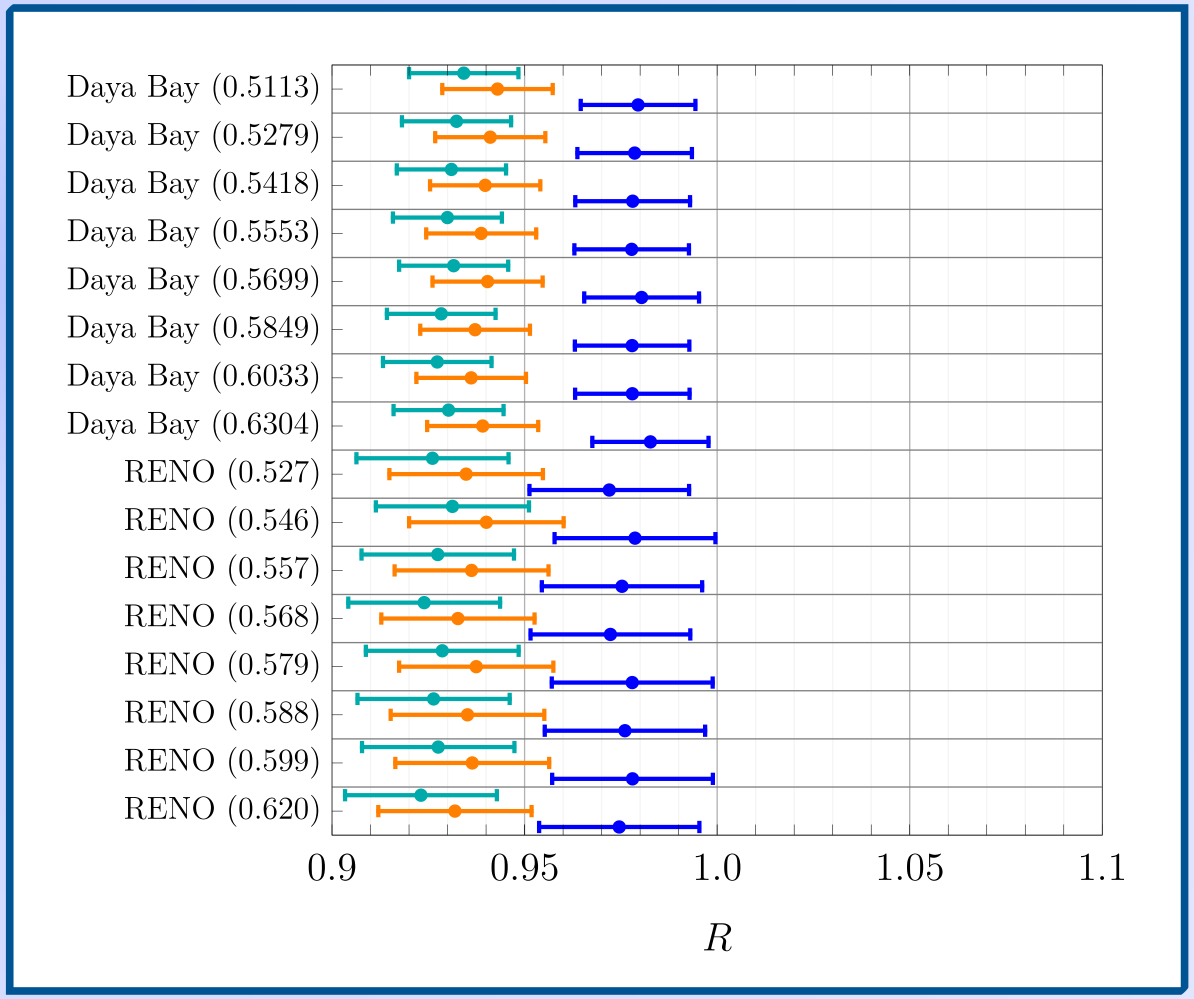


FIG. 1. (Color online) Shown is the relative size of the various corrections listed in equation 4 for a hypothetical β-decay with $Z = 46$, $A = 117$ and $E_0 = 10\,\mathrm{MeV}$. The upper panel shows the effect on the neutrino spectrum, whereas the lower panels shows the effect on the β-spectrum.

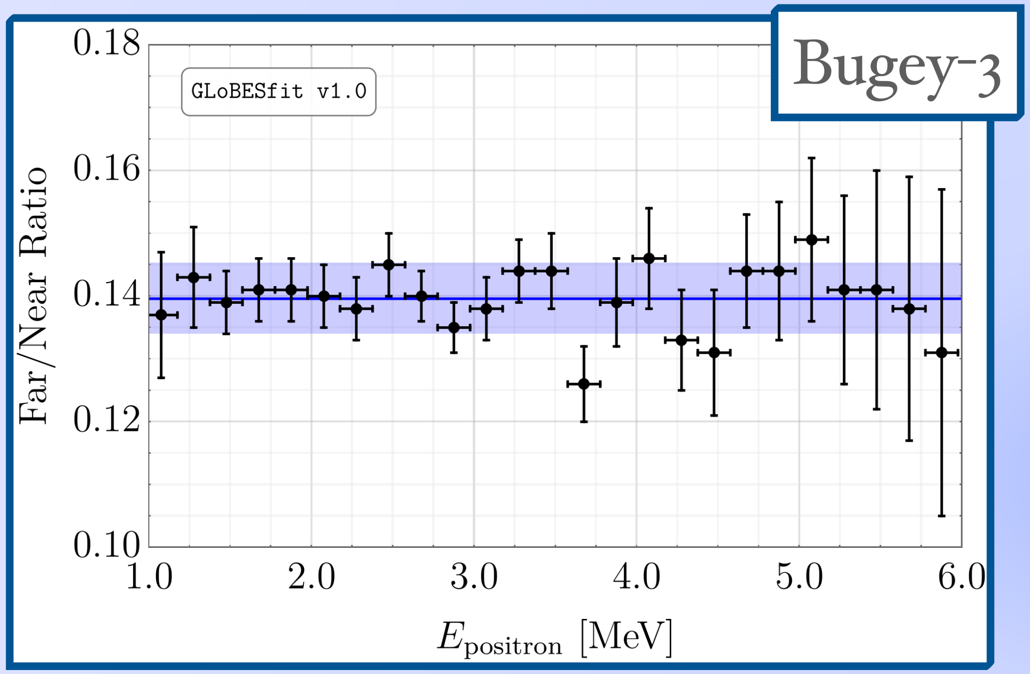
P. Huber, PRC 84 (2011) 024617 (Erratum: PRC 85 (2012) 029901)

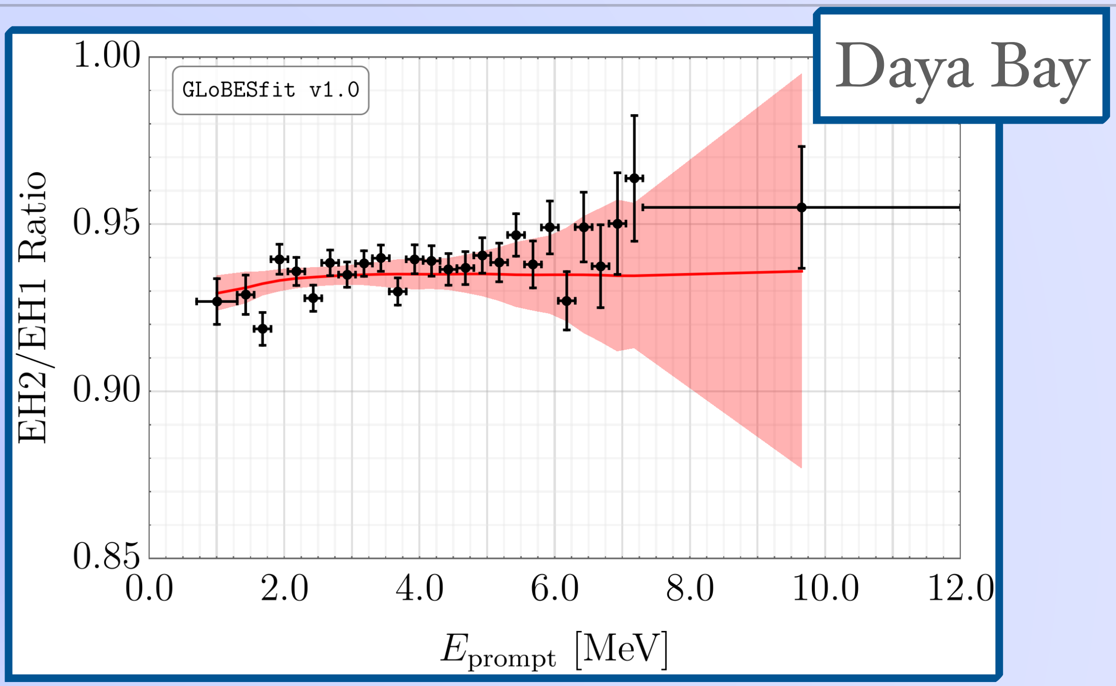
Rate Measurements

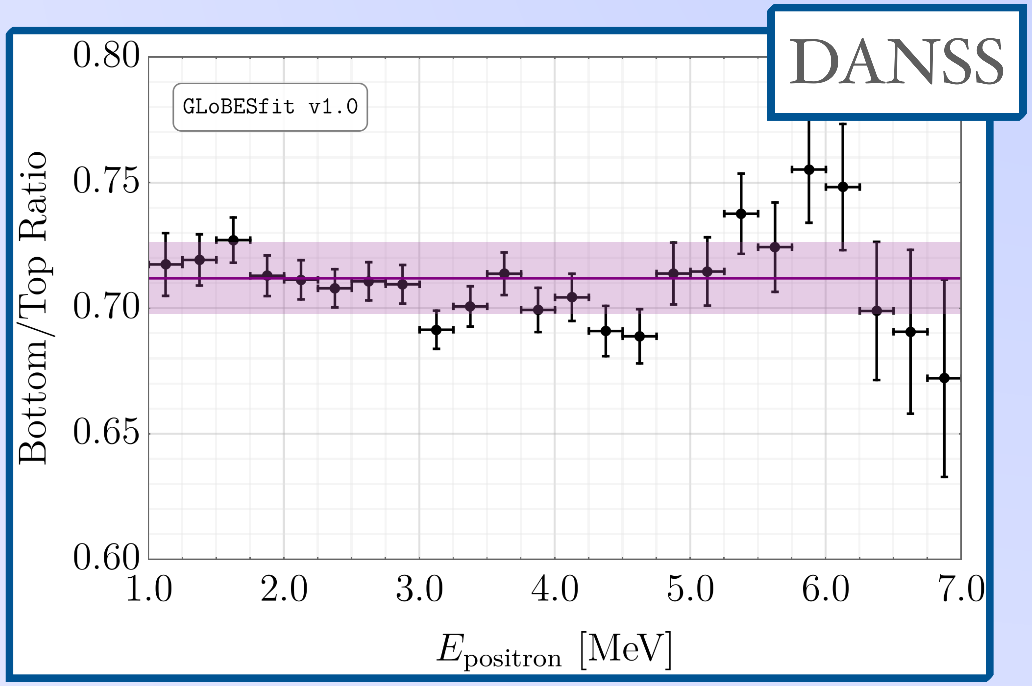


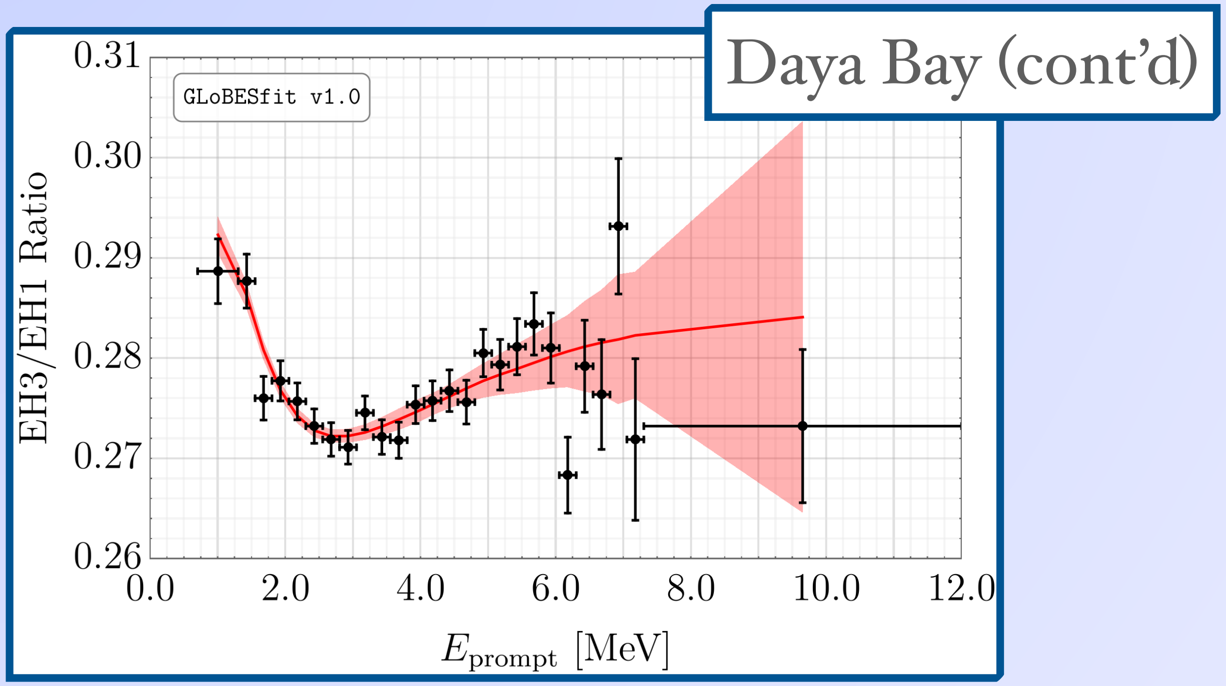


Spectrum Measurements

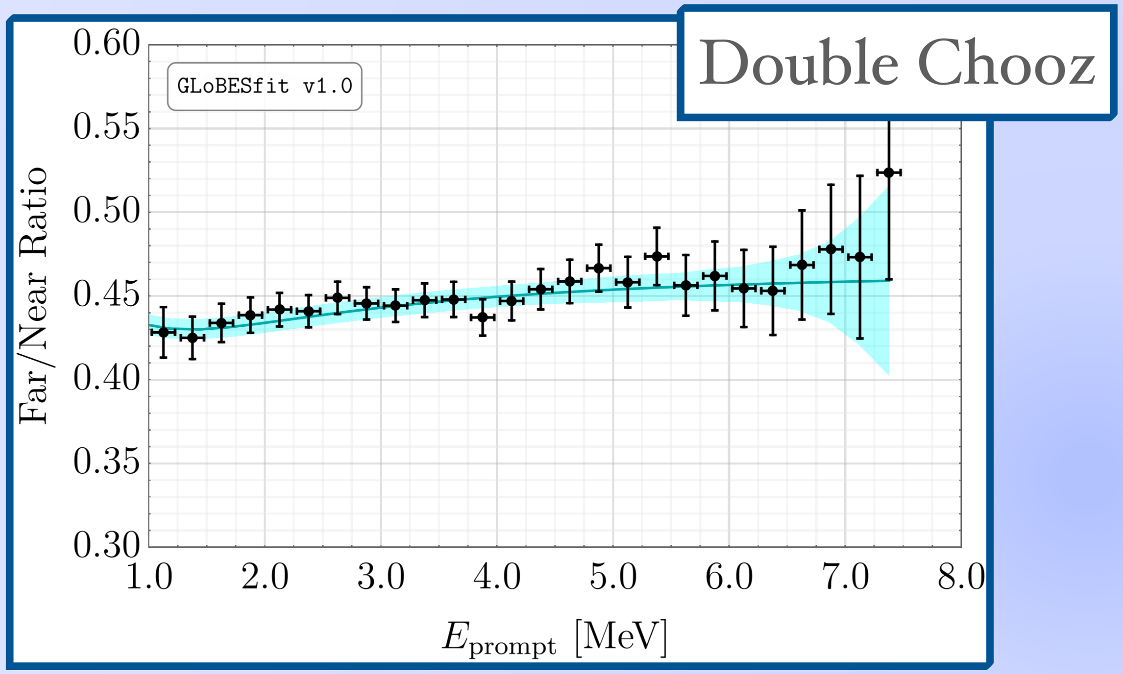


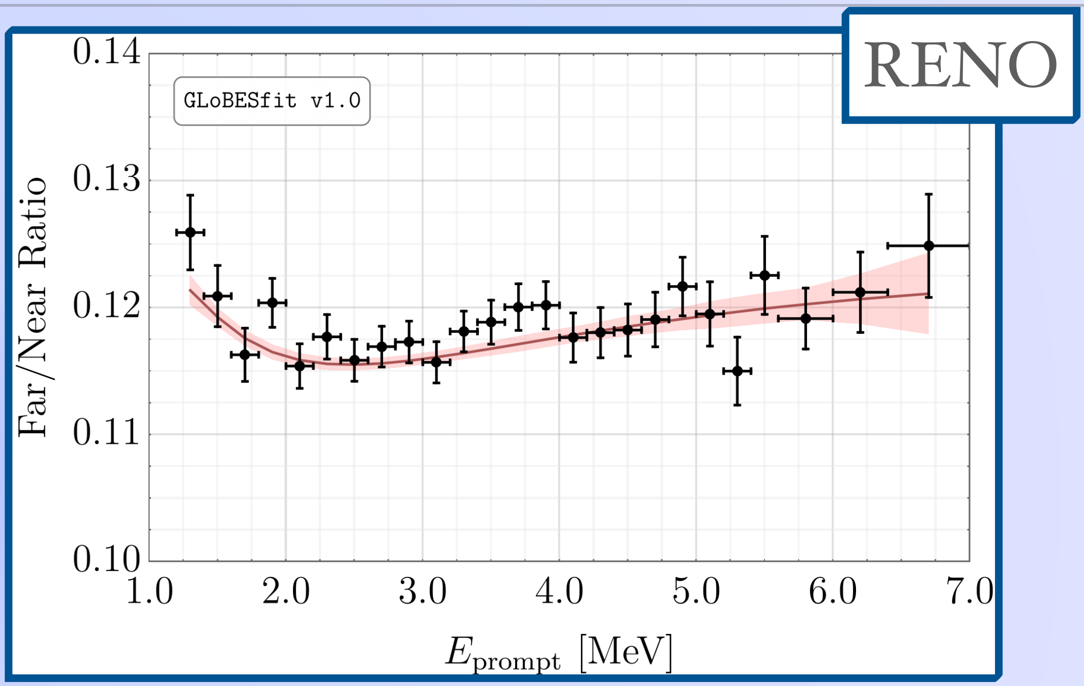


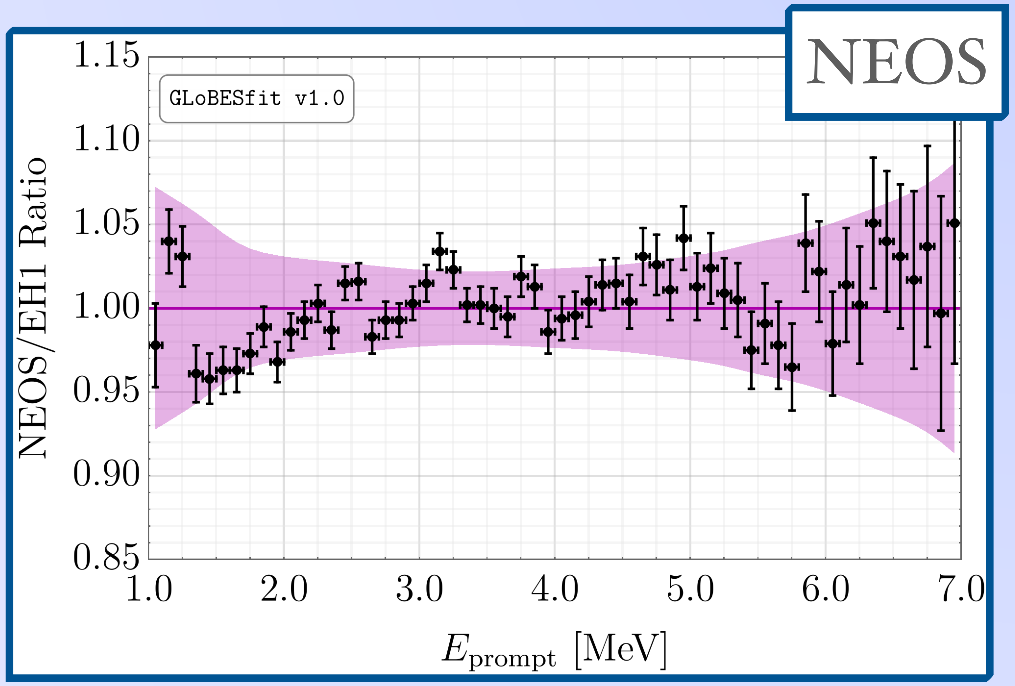




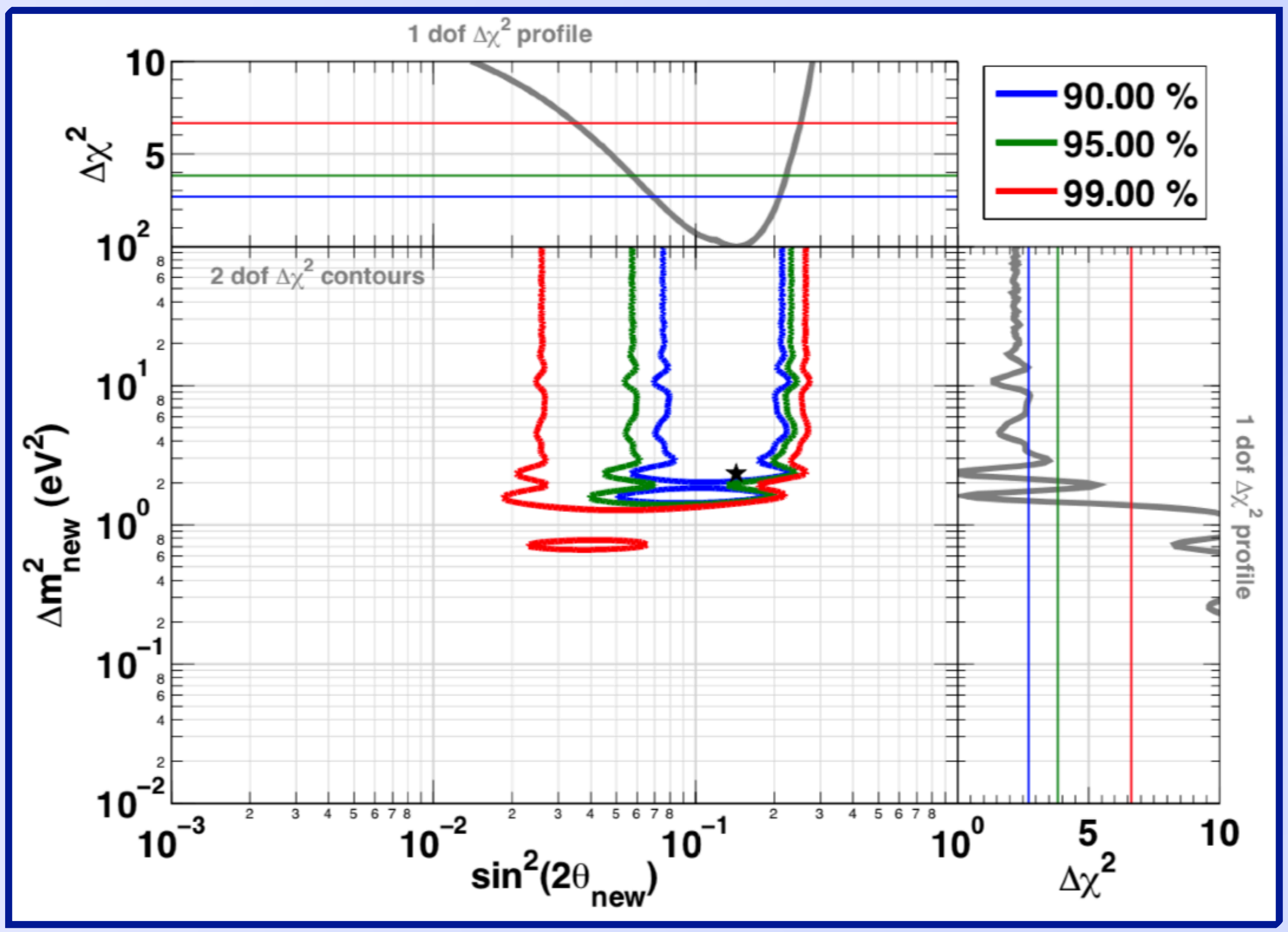
Spectrum Measurements

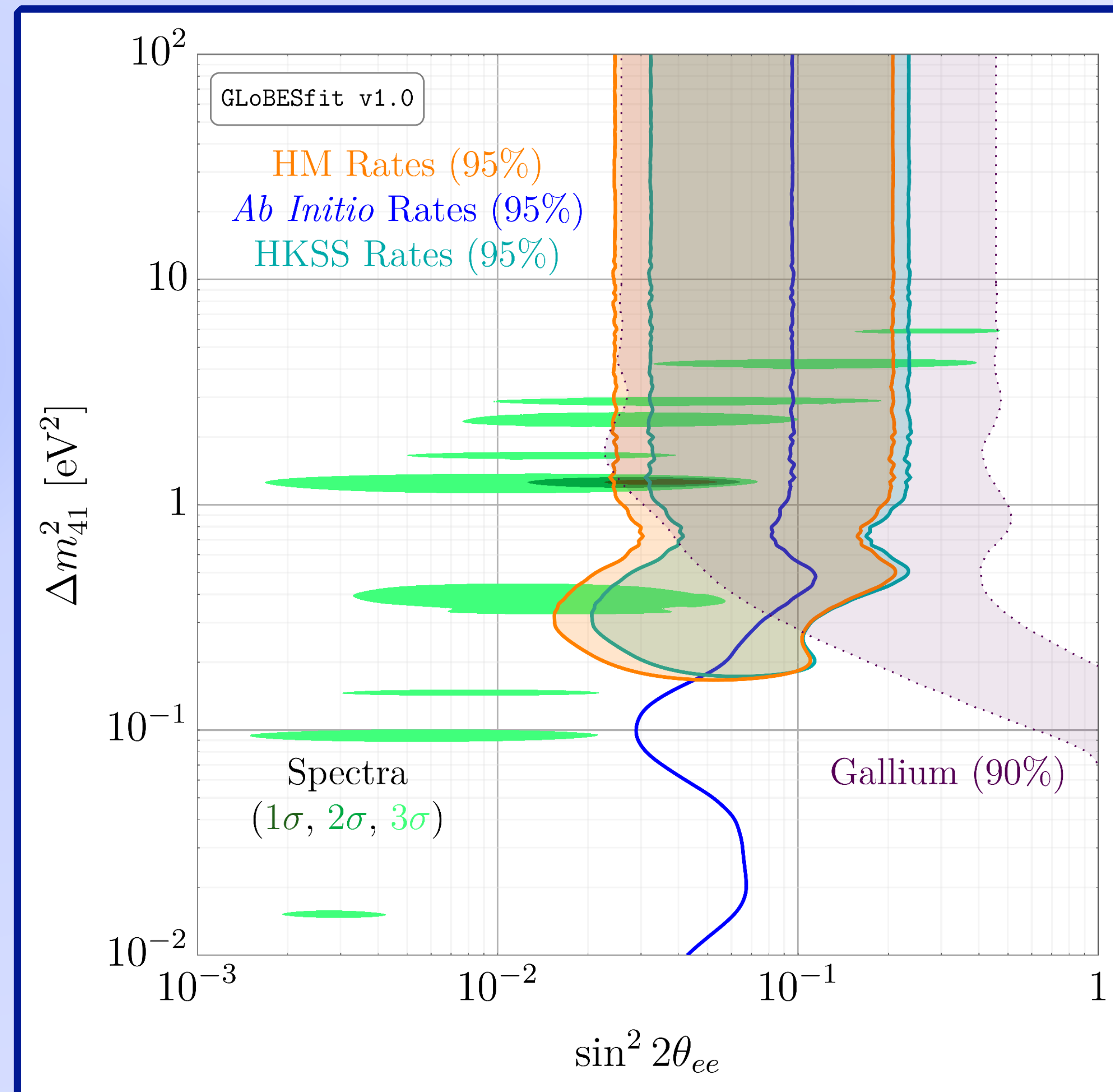






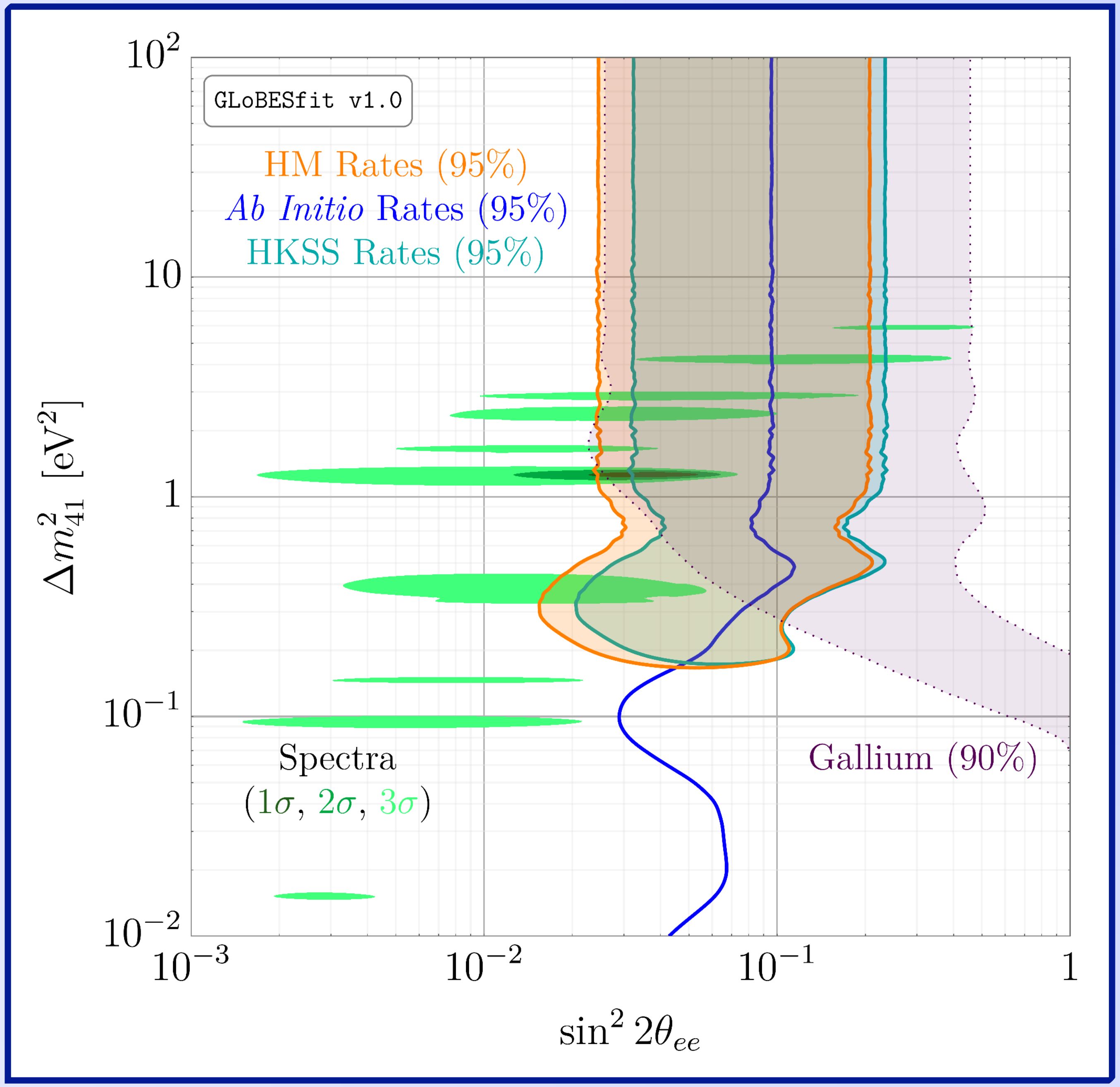
Comparing Global Analyses

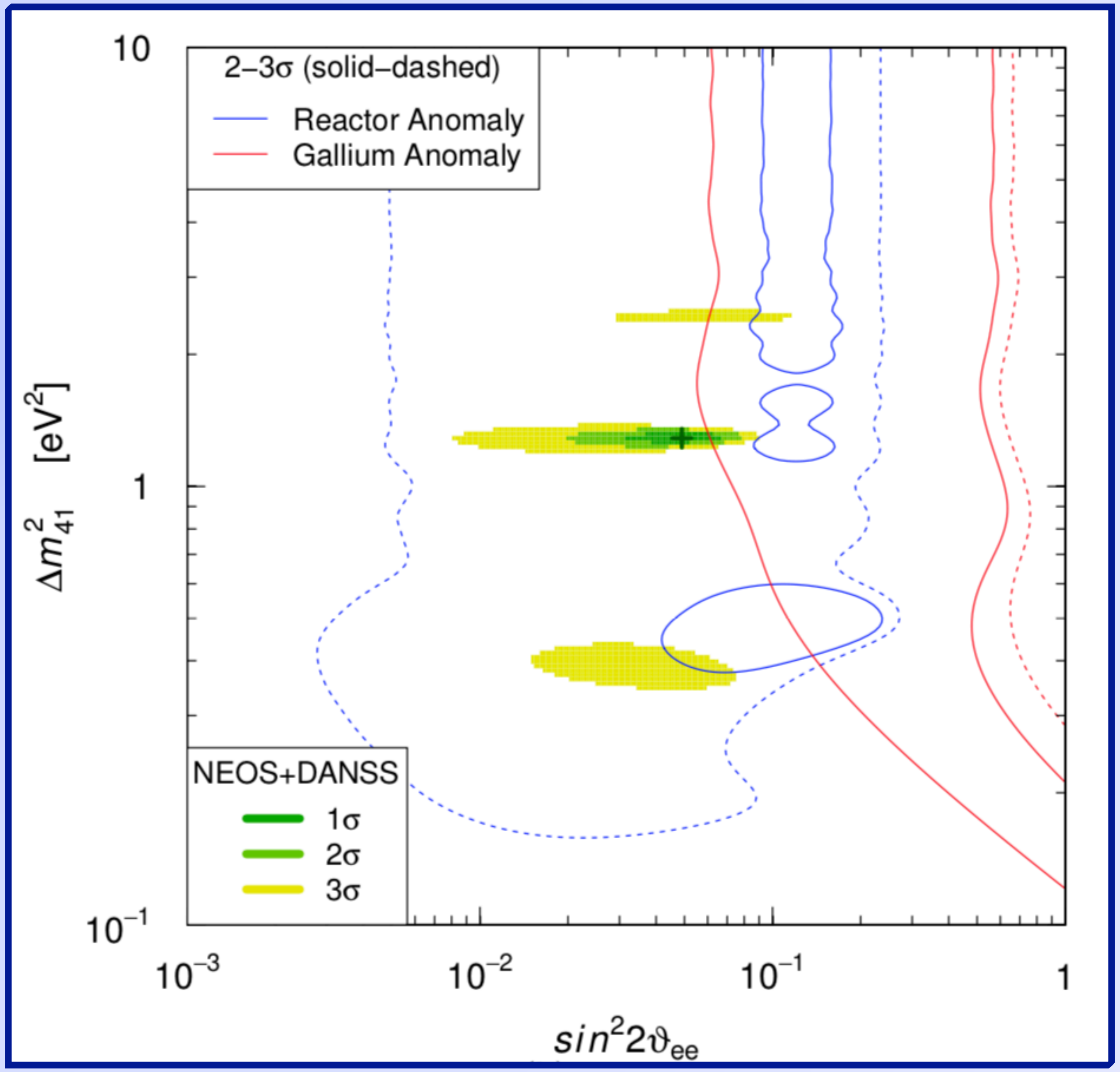




G. Mention, et al., PRD 83 (2011) 073006;
J. Kostensalo, et al., PLB 795 (2019) 542

Comparing Global Analyses





J. Kostensalo, et al., PLB 795 (2019) 542 ; S. Gariazzo, et al., PLB 782 (2018) 13; M. Dentler, et al., JHEP 08 (2018) 010; Giunti, et al., PRD 99 (2019) 073005; A. Diaz, et al., arXiv:1906.00045

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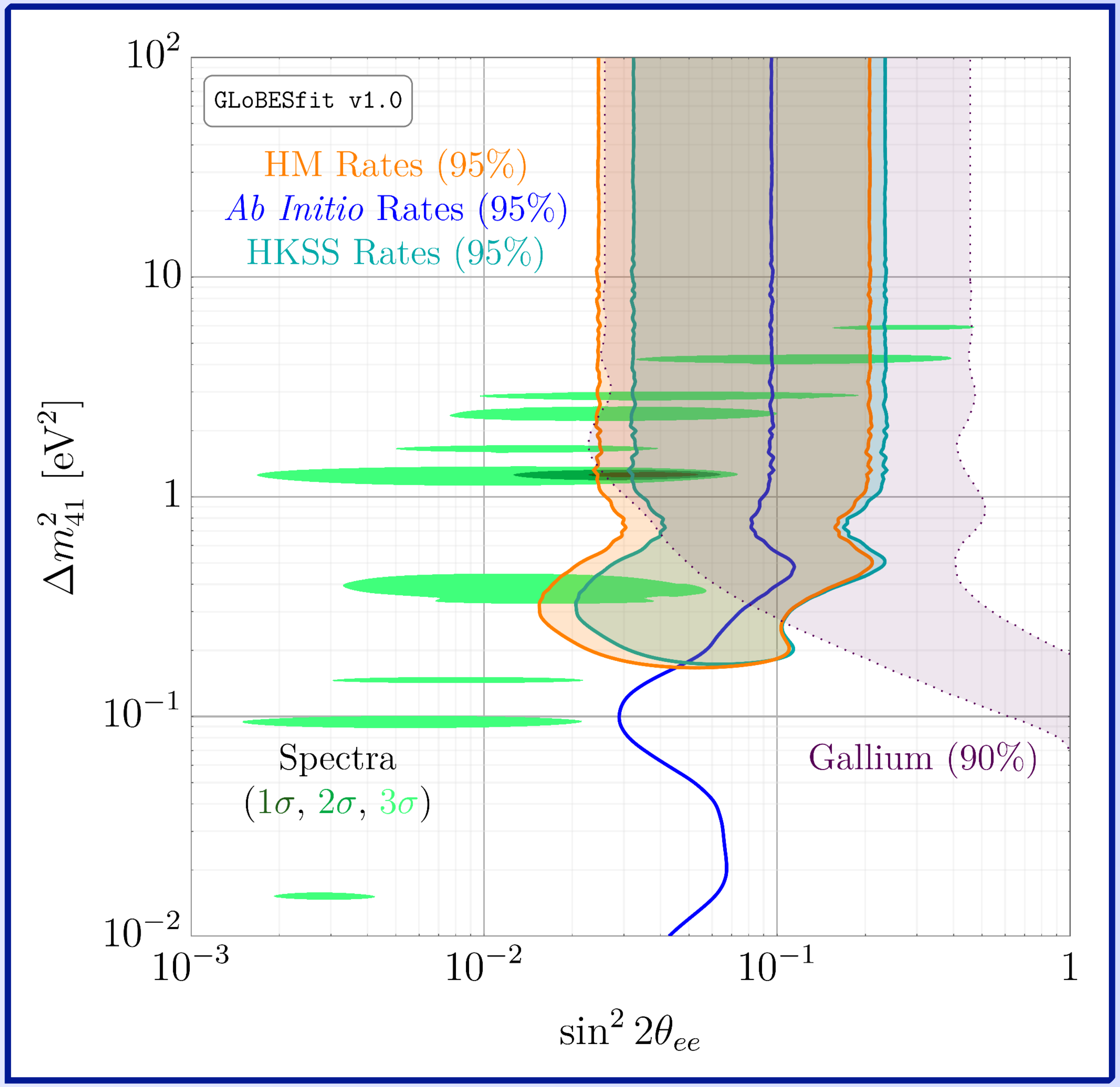

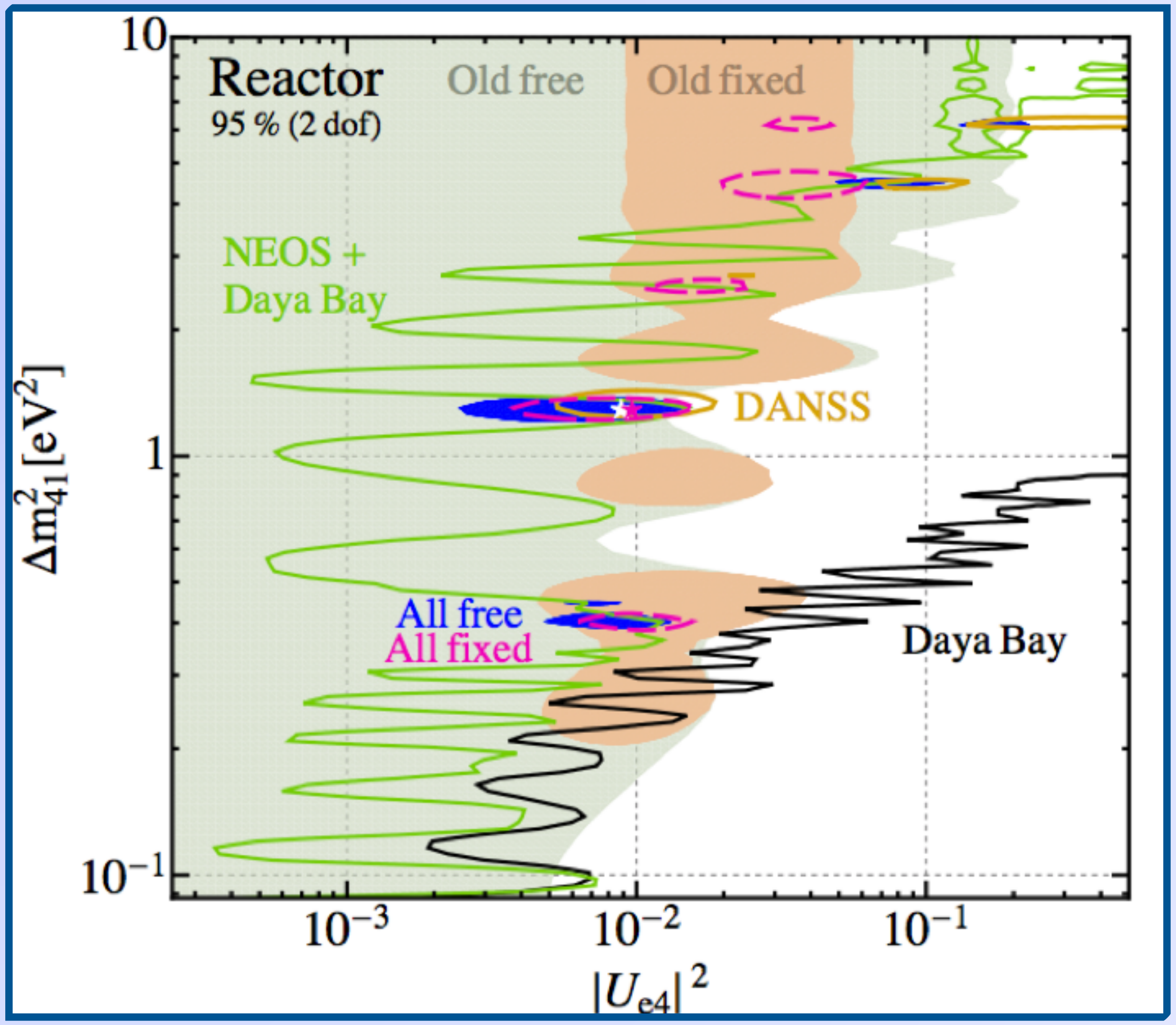

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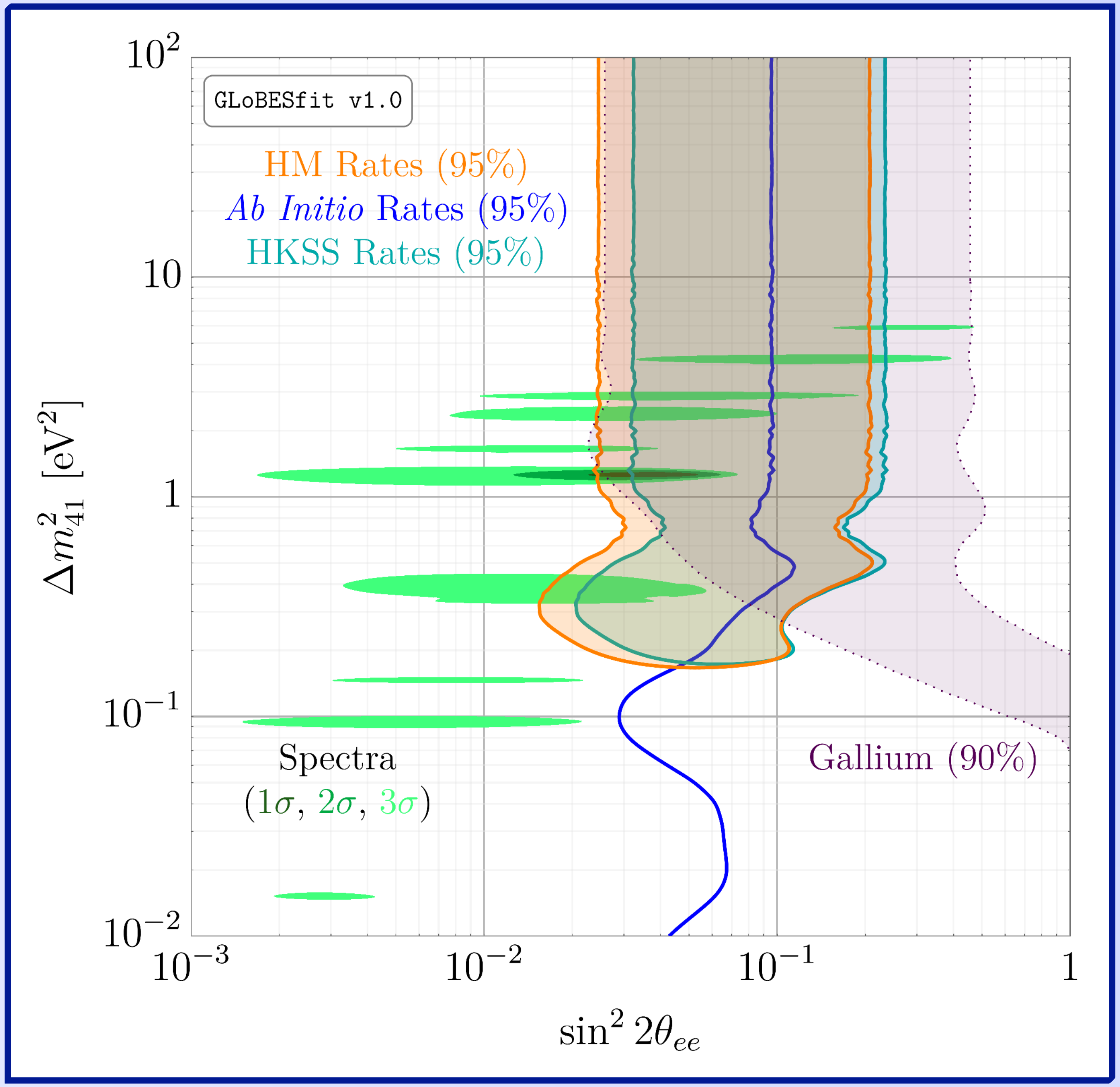
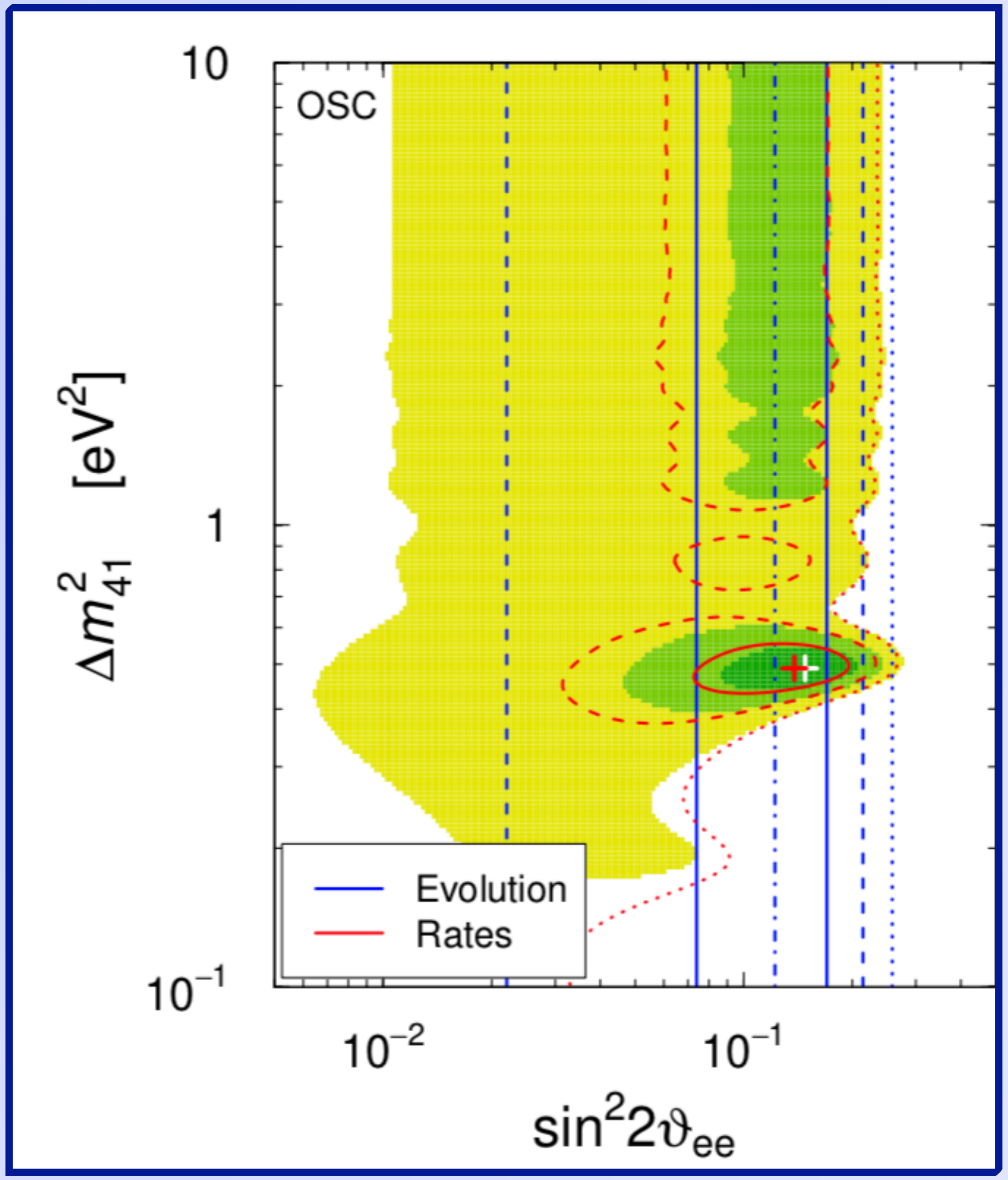
Comparing Global Analyses





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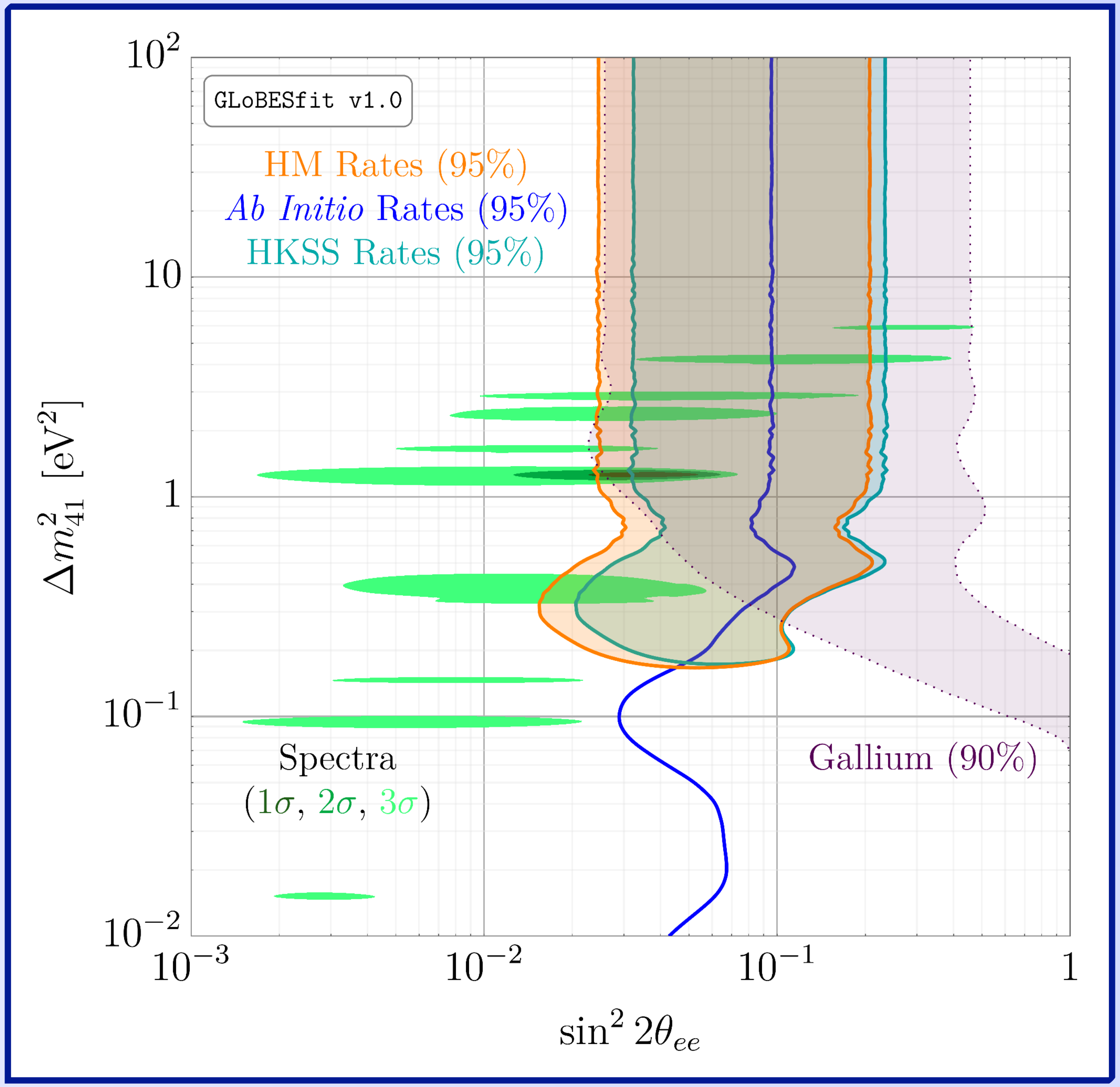
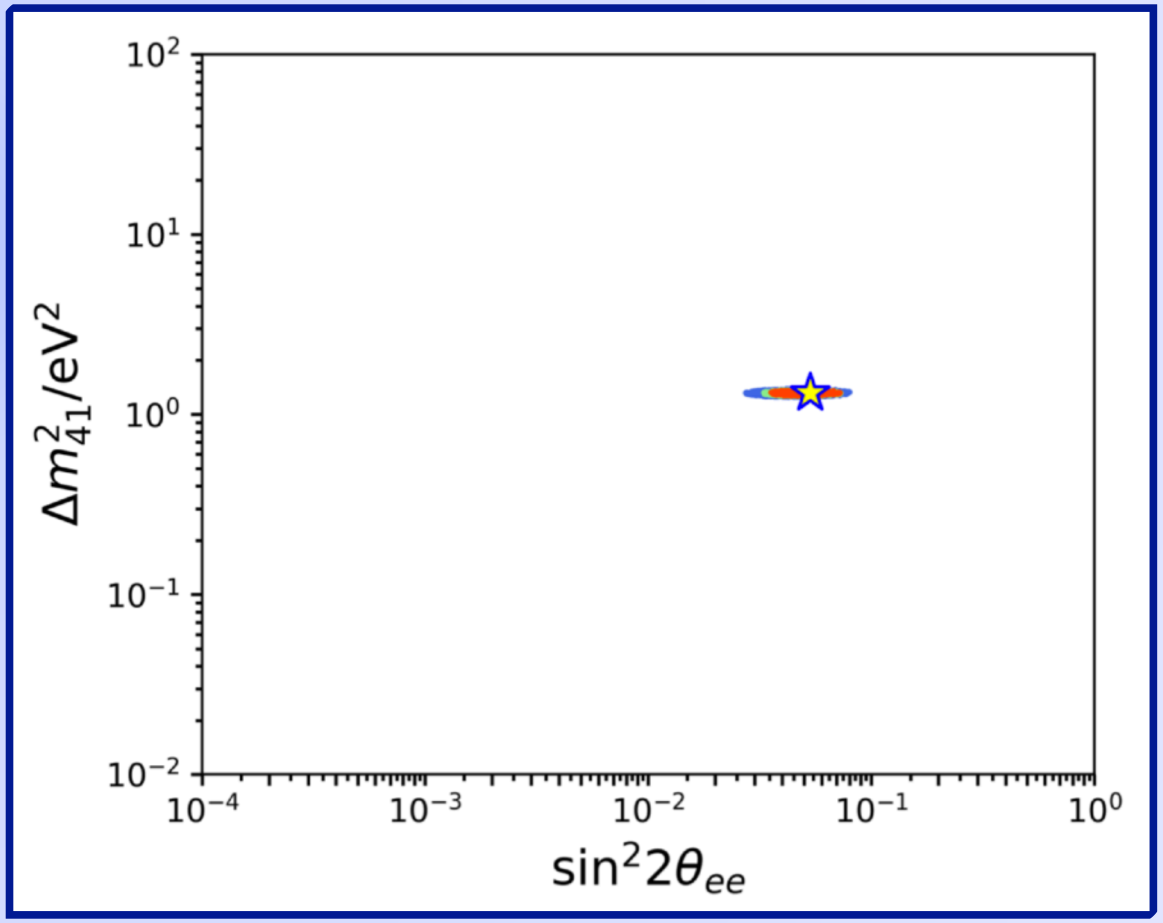
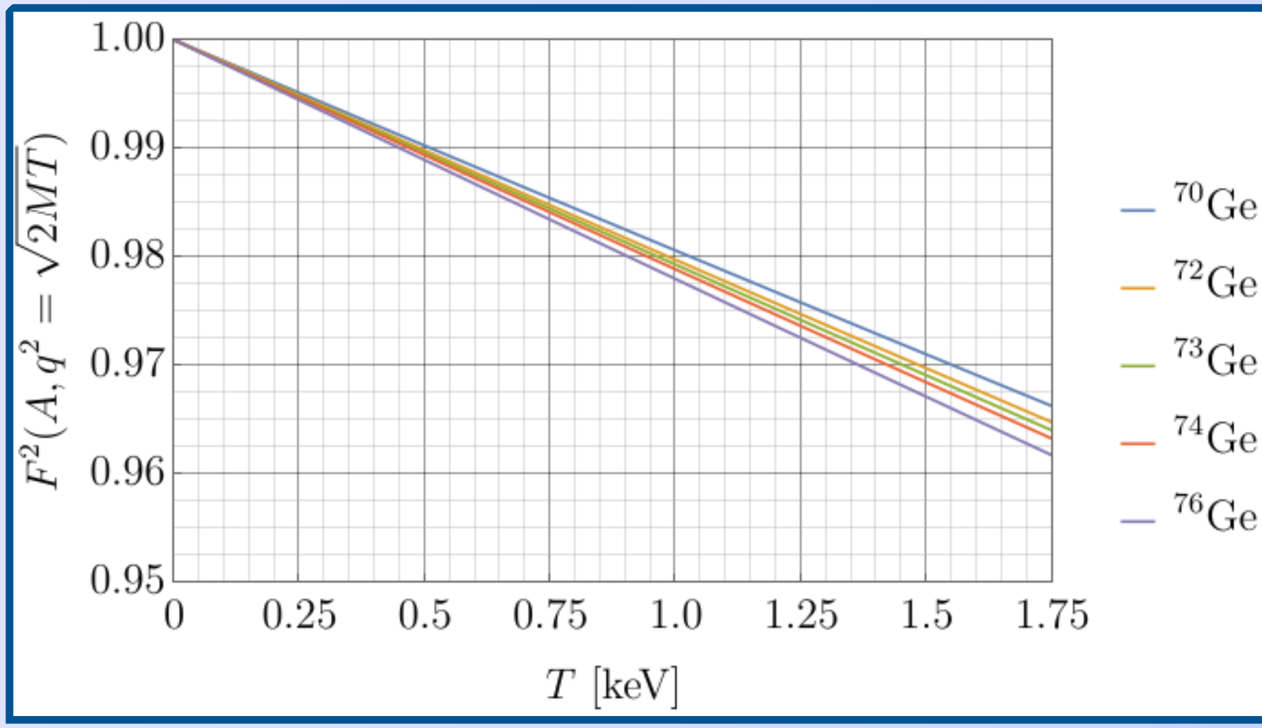
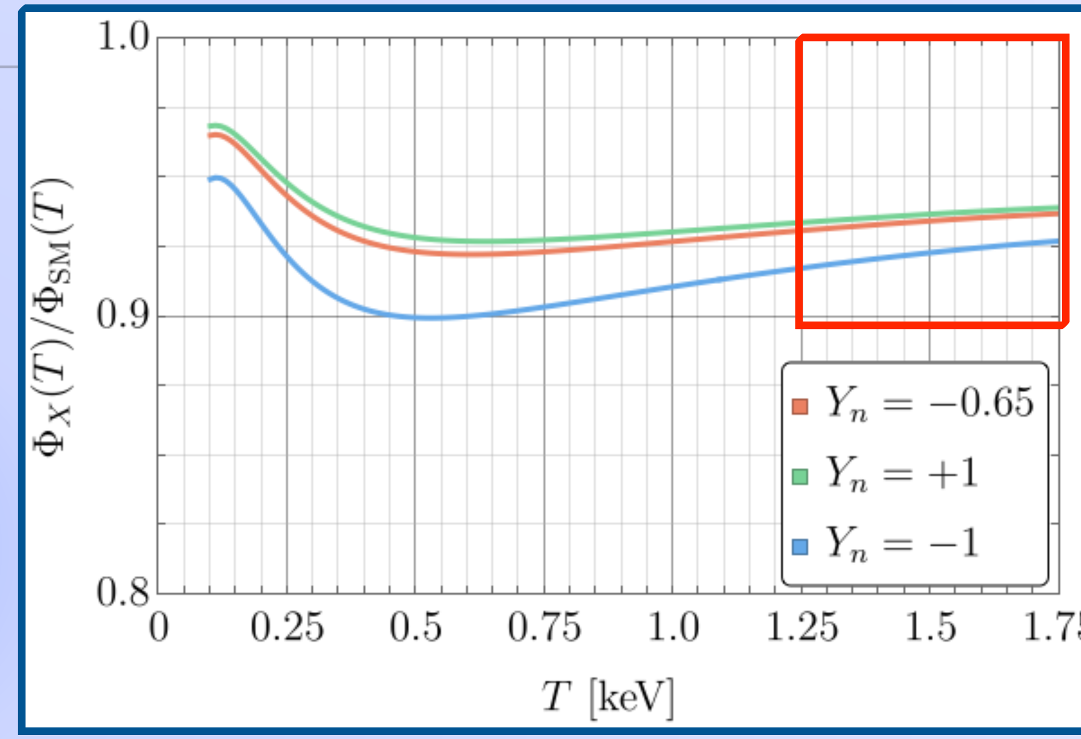




J. Kostensalo, et al., PLB 795 (2019) 542 ; S. Gariazzo, et al., PLB 782 (2018) 13; M. Dentler, et al., JHEP 08 (2018) 010; Giunti, et al., PRD 99 (2019) 073005; A. Diaz, et al., arXiv:1906.00045

CONUS Analysis: Details





$$N_i = \sum_{\{(N,Z)\}} \Delta t\, N_{(N,Z)} \int_{E_r^i}^{E_r^i+\Delta E_r} dE_r \int_{0\ \text{MeV}}^{8\ \text{MeV}} dE_\nu\, \Phi(E_\nu) \frac{d\sigma}{dE_\nu} \times \Theta\left(2E_\nu^2/M_{(N,Z)} - E_r\right)$$

$$\chi^2 = \sum_i \frac{\left(N_i^{\text{SM}} - (1+\alpha) N_i^{\text{NP}}(g_X, M_X)\right)^2}{\sigma_{\text{stat},\, i}^2 + \sigma_{\text{sys},\, i}^2} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2$$

~2%

$$\sigma_{\text{stat},\, i} = \sqrt{N_i^{\text{SM}} + N_i^{\text{bkg}}} \qquad \sigma_{\text{stat},\, i} = \sigma_f \left(N_i^{\text{SM}} + N_i^{\text{bkg}}\right)$$

Y. Farzan, et al., JHEP 05 (2018) 066

CONUS vs. CONUS100

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} P_{ee} Q_{\rm eff}^2 F_{\rm Helm}^2(q^2) \left(1 - \frac{MT}{2E_\nu^2}\right)$$

$$N_i = \Delta t \sum_f n_f \int_{T_i}^{T_i+\Delta T} dT \int_0^\infty dE_\nu \Phi(E_\nu) \frac{d\sigma_f}{dT} \Theta(2E_\nu^2 - MT)$$

$$\chi^2 = \sum_i \frac{\left(N_i^0 - (1+\alpha) N_i(\sin^2 2\theta_{ee}, \Delta m_{41}^2)\right)^2}{N_i + N_{\rm bkg} + \sigma_f^2 \left(N_i + N_{\rm bkg}\right)^2} + \frac{\alpha^2}{\sigma_\alpha^2}$$

- CONUS: 4.0 kg natural Ge; $T \in [1.2, 1.75]\,\mathrm{keV}$; $\sigma_\alpha = 0.02$; $\sigma_f = 0.01$; one year of running
- CONUS100: 100.0 kg enriched Ge; $T \in [0.1, 1.75]\,\mathrm{keV}$; $\sigma_\alpha = 0.005$; $\sigma_f = 0.001$; five years of running
- Background rate: 1 count/(day*keV*kg)

Y. Farzan, et al., JHEP 05 (2018) 066;
V. I. Kopeikin, Phys. Atom. Nucl. 75 (2012) 143